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AN ASSESSMENT METHODOLOGY FOR THE ENVIRONMENTAL
IMPACT OF WATER RESOURCE PROJECTS

BATTELLE COLUMBUS LABORATORIES

PREPARED FOR
WASHINGTON ENVIRONMENTAL RESEARCH CENTER

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This report presents materials intended for use by reviewers of environmental impact statements on major water resources development reservoir projects. The report is prepared as a series of six related but individually referenced discussions of the following major topics:

- Reservoir project planning, construction, and operation activities;
- Water quality impacts of reservoir construction;
- Ecological impacts of reservoir construction;
- Economic, social, and aesthetic impacts of reservoir construction;
- Review criteria for assessing general statement completeness and accuracy; and
- A review of impact assessment methodologies.

The materials presented attempt to call to the reviewer's attention important issues or potential impacts that an adequate impact statement should address. In addition, the water quality and ecological impacts sections discuss the site-specific conditions under which a given potential impact may or may not occur.

The section on water quality impacts also presents a detailed comparison of mathematical models for predicting impacts on water temperature, dissolved oxygen levels, and some chemical constituents of surface waters. The sections dealing with water quality, ecological, and economic-social-aesthetic impacts include extensive citations to relevant literature the impact statement reviewer may wish to consult for further information.

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AN ASSESSMENT METHODOLOGY FOR THE ENVIRONMENTAL
IMPACT OF WATER RESOURCE PROJECTS

By

Maurice L. Warner, John L. Moore, Samar Chatterjee,
David C. Cooper, Christopher Ifeadi, William T. Lawhon,
and Robert S. Reimers

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Project Officer

Harold V. Kibby
Washington Environmental Research Center
Washington, D.C.

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FOREWORD

The wide spread use of environmental impact analysis as a means of making Federal agencies decisions responsive to environmental concerns was initiated by the passage of the National Environmental Policy Act of 1969. The Act required that Federal agencies prepare statements assessing the environmental impact of their major actions which significantly affect the quality of the human environment. The Council on Environmental Quality recently developed guidelines to define uniform procedures and approaches in the preparation of environmental impact statements (EIS). While these guidelines specify what is desired in Federal impact statements, technical approaches to meeting these objectives are not always available and universally acceptable.

Under Section 309 of the Clean Air Act, the U.S. Environmental Protection Agency (EPA) is required to review, in writing, all EIS's prepared by Federal agencies. Among the several obstacles to the meaningful review of EIS's, has been the lack of consistency between reviewers and the lack of standardized procedures for undertaking reviews. The EPA Office of Federal Activities has undertaken the task of writing a series of review guidelines for various classes of EIS's.

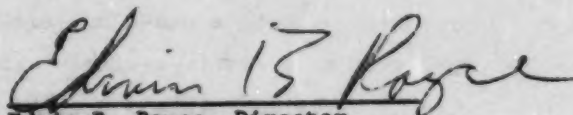
As part of the Socioeconomic Environmental Studies, the Office of Research and Development is conducting research to support both the preparation and review of EIS's. Specifically, this research is designed to:

Improve the ability of the Agency to
provide substantive technical review
of EIS's prepared by other agencies.

- Improve the technical quality of environmental impact analysis in areas of agency responsibility.

- Improve the effectiveness of the use of environmental impact analysis in influencing decision-making at all governmental levels.

This report contains a review of the potential impacts associated with the construction and operation of large water impoundments. It was conducted by the Battelle Columbus Laboratories under contract from the Washington Environmental Research Center, Office of Research and Development, Environmental Protection Agency. The work was supported by the Ecological Impact Analysis Staff.



Edwin B. Royce, Director
Ecological Impact Analysis Staff

ABSTRACT

This report presents materials intended for use by reviewers of environmental impact statements on major water reservoir projects. The report is prepared as a series of six related but individually referenced discussions of the following major topics:

- Reservoir project planning, construction, and operation activities
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- Ecological impacts of reservoir construction
- Economic, social, and aesthetic impacts of reservoir construction
- Review criteria for assessing general statement completeness and accuracy
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This report was submitted in fulfillment of Contract 68-01-1871, by Battelle's Columbus Laboratories, under the partial sponsorship of the Environmental Protection Agency. Work was completed as of May 1974.

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SECTION I

INTRODUCTION

This report presents a variety of technical materials intended for use in reviewing environmental impact statements (E.I.S.) on major reservoir construction projects. These materials are to assist the E.I.S. reviewer in determining the completeness and accuracy of such statements with special emphasis on water quality and ecological impacts. Since the potential users of this material have a wide variety of backgrounds and must deal with the full range of environmental conditions in the U.S. in which reservoirs may be constructed, the materials in this report are necessarily general in nature. Numerous citations to useful literature on more specific project situations are provided.

Section II through VII of this report present interrelated topics but are written to be useful as free-standing documents as well. Each section contains a separate list of references (except Section II and VI where no specific literature is cited). Each section is summarized below.

Section II, "Reservoir Project Activities", presents brief descriptions of the basic activities associated with planning, construction, and operation of major reservoir projects. The major differences between projects constructed to serve different purposes (e.g. flood control vs. water supply vs. recreation, etc.) are also described. This section serves as a general overview to give the E. I. S. reviewer a better grasp of the full extent of project activities with possible environment impacts.

Section III, "Water Quality Impacts Resulting from Reservoir Construction", presents a detailed technical discussion of predictive techniques that are used to project possible water quality impacts of reservoir construction. The impacts that are addressed include the broad areas of water temperature impacts, dissolved oxygen

impacts and impacts on chemical constituents of the water. The emphasis in this section is on comparison of the various predictive techniques and models presented to provide the reviewer with guidance on the appropriateness of any particular technique in a specific project situation.

Section IV, "Ecological Impacts Resulting from Reservoir Construction", provides the reviewer with information on the variety of impacts a reservoir project may have upon terrestrial and aquatic ecosystems. Since the magnitude, significance, and even the occurrence or non-occurrence, of any single impact depends so highly on site-specific conditions, this section is organized around general categories of ecological impacts. For each category, emphasis is placed on specific impacts experienced in the past as reported in the literature, and on questions an EPA reviewer might ask to estimate the likelihood and magnitude of an impact in a specific project situation. Additional attention is given to the problem of impact measurement.

Section V, "Economic, Social, and Aesthetic Impacts Resulting From Reservoir Construction", deals in a more general way with socio-economic impacts and the relevant literature. The section identifies a variety of impacts that may be produced by a project and gives citations to literature dealing more fully with each impact. No attempt is made to define specific techniques for quantitatively predicting economic, social, and aesthetic impacts.

Section VI, "Review Criteria", presents a set of guidelines a reviewer may use to assess the completeness and accuracy of an environmental impact statement as a whole. In contrast to Sections III - V, Section VI does not address any single area of potential environmental impacts.

Section VII, "A Review of Environmental Impact Assessment Methodology", presents a summary and critical review of 17 frameworks or tools for impact assessment. These 17 range from comprehensive "how to" manuals for conduct of an assessment to single conceptual tools that have been or may be applied to specific aspects of the impact assessment task. It is hoped that this section will provide the EPA reviewer with some perspective on the state-of-the-art in impact assessment.

These various sections are not organized into a step-by-step E. I. S. review procedure or manual. It is expected that such a manual will be prepared by EPA staff members, integrating information provided in this report with the operating practices and statutory obligations of the Environmental Protection Agency.

SECTION II

WATER RESOURCE PROJECT ACTIVITIES

In order to identify and evaluate impacts associated with reservoirs, it is first necessary to establish a general list and description of project activities. Each water resource project consists of several different types of activities having a variety of environmental impacts. Major categories of activities are

- (1) Planning
- (2) Construction
- (3) Operation (including maintenance and project output).

Planning involves a whole gamut of activities that are undertaken prior to ground-breaking and building of the project. Construction involves those activities which create physical structures and actions in accordance with the approved design. After the project has been partially or completely built, it is operated in accordance with the approved design specifications and operating procedures to produce the specified project output. The maintenance of a water resource project involves activities that are undertaken during the period of operation to ensure that the safety, stability, and environmental desirability of the system is maintained.

A "list" of specific activities within each general category (planning, construction, and operation) is presented below. General descriptions of the types of impacts associated with each category are also provided in this section. Detailed discussions of water quality and ecological impacts are presented in Sections III and IV of this report, respectively. A less detailed discussion of socioeconomic impacts is presented in Section V.

PLANNING

The planning process, per se, will not have any direct adverse effects on the major focus of this research project; namely, ecological

and water quality impacts. Planning activities such as those listed below, however, can have very definite socioeconomic impacts.

- Public need assessment
- Reconnaissance
- Public hearings
- Design studies
- Project design.

Those socioeconomic impacts which occur at the planning stage are due to anticipation of future reservoir related changes. For example, conflict among opposing interest groups over the desirability of the reservoir may result in deterioration of community cohesion. Speculation in land adjacent to or below the proposed reservoir may be another impact which occurs at the planning stage. Major opposition to the project by those who would be displaced will also probably take place before land is acquired and construction begun.

Since most of the socioeconomic impacts that occur at the planning stage relate to anticipated environmental or economic alterations, no explicit description of planning activities is considered necessary. In reviewing impact statements, however, the analyst should consider the extent to which anticipation of future changes may cause explicit socioeconomic impacts which precede construction and operation of the reservoir.

CONSTRUCTION

Construction involves those activities which create physical structures and land alterations in accordance with the approved project design. These activities are:

- Land acquisition
- Relocation of families
- Power line construction
- Flood protection/drainage works construction
- Access road construction
- Canal construction

- Site/foundation preparation
- Rock blasting/drilling
- Demolition of existing structures
- Soil/debris disposal
- Quarrying and stone work
- Concrete batching/placement
- Embankment construction
- Dam construction by various methods
- Outlet construction
- Spillway construction
- Stream bed protection
- Surface finishing
- Landscaping.

These activities cause a variety of physical/chemical, ecological, aesthetic, and socioeconomic impacts of varying durations and degrees. Physical/chemical changes occur during construction primarily as a result of clearing and stripping of vegetative cover on the reservoir site. This stripping process exposes soil to erosion thus increasing turbidity in receiving waters. In most cases stream temperature is also raised. The rate of basin runoff is also altered during the construction phase due to vegetative removal. Ecological impacts include primarily the destruction of supportive habitat for a variety of organisms. Clearing of the site will remove forest and fields habitat resulting in the displacement and outright destruction of terrestrial organisms. These are, of course, long lasting or permanent changes in habitat subject only to eventual dismantling of the reservoir and return of river flow to a normal channel. Aquatic ecology would also be altered in the process of reservoir construction. These alterations will relate to the turbidity and erosion problems created during construction as well as the impacts from increased water temperature, increased runoff rates, downstream sedimentation, and physical removal of habitat due to straightening and/or alignment of channels. Aesthetic impacts relate to the alteration of the existing natural and man-made landscape and to the introduction of various types of man-made structures. The appearance of

existing landscape will be altered due to removal of trees, land shaping, and temporary exposure of various types of soil at the reservoir site. Various man-made objects will be introduced, including various forms of access roads, power lines, the dam structure itself, and any related support facilities. Amenity factors, such as odor and noise, may also be affected during reservoir construction. Socioeconomic impacts during the construction phase relate primarily to the effects on persons displaced from the reservoir site; to the disruption and blocking of various public utilities, roads, and other infrastructure important to adjacent communities; to removal of land from its present use; to destruction or removal of cemeteries, historical buildings and sites or unique natural resources or attributes of the site, and to destruction of recreation areas associated with free flowing streams. These construction related alterations will have particular effects on community cohesion and social activity patterns.

Definitions and descriptions of the general activities that can cause the above types of impacts are presented below.

Land Acquisition

Water resources projects involving reservoirs, canals, etc., involve large tracts of land that must be acquired for physical project use. Creation of a reservoir across a natural channel can flood a large tract of land upstream. Construction of canals requires land for its right-of-way. These lands may be acquired by fee simple title, by condemnation, easement, etc.

Relocation of Families

Before actual construction of structures can begin on a water resource project, the people living on the acquired land must be relocated elsewhere, possibly on nearby land. This important issue has frequently been a major cause of opposition to water resource projects. The current opposition and distrust of government action in regard to

relocation of families is based on precedent. As Morgan (1971) points out, there has been a pattern of improper and unjust handling of displaced families, especially the Indian population.

Power Line Construction

The large majority of water resource projects consume considerable amounts of energy during construction and during operation. Therefore, a power line must be constructed from a major source of power to the site. Generally towers are used to carry high tension lines across country long distances to the construction and operation site.

Flood Protection/Drainage Works Construction

Construction of dams generally involves creation of temporary flood protection and drainage works that will protect the dams and embankments against high floods during construction. These protection works can have different configurations. They may involve construction of a coffer-dam which prevents flood water from entering the construction site, or construction of a diversion tunnel that diverts the flood waters away from the construction site, thus preventing flood damage to the incomplete structures.

Access Roads Construction

Frequently, water resource projects including dams and reservoirs are built in natural areas that are not accessible by land transportation. In the first phase of construction, temporary roads are built that provide access to various critical locations of the project where men and materials must be deployed to construct and operate the project. These temporary access roads are generally unpaved.

On completion of the project, some of these roads, which are needed during operation and maintenance, are paved and turned into permanent roads. Many other stretches of the access roads not needed during project operation and maintenance are abandoned, occasionally resulting in significant soil or slope erosion problems.

Canal Construction

Construction of canals involves major operations of digging and filling over a large area. Canals are used to carry water from the reservoir to distant arable land which is unproductive or less productive due to the scarcity or shortage of water. Generally, canals are artificial channels cut to transport irrigation water.

Site/foundation Preparation -

Preparation of the foundation is an essential feature in the proper design of dams and reservoirs. The foundations must be designed to restrict excessive foundation pressures, to provide necessary sliding resistance, and to maintain flexibility without loss of structural strength. The foundation on which reservoirs are built are of five general types: rock, pervious soil, impervious soil over rock, impervious soil over pervious soil, and stratified soil. Different types of foundations require different kinds of preparation or treatment for construction and maintenance safety.

Site Clearance -

A natural reservoir site generally has extensive vegetation, trees, soft uncompacted soil, and other features not suitable as a stable foundation for a reservoir. Site clearance involves removing or clearing all vegetation on top of the soil. In this activity only the vegetation on top of the soil is removed.

Grubbing -

Grubbing is a specific operation which begins after site clearance and involves removal of tree stumps and roots.

Stripping of Top Soil

Generally the top soil has a weaker texture than subsoil. It has a high degree of organic content and is therefore subject to a high degree of settlement. Also, it may be impervious or subject to swelling as a result of exposure to water. It is, therefore, essential to remove the top soil in the area on which a reservoir foundation is built. Generally, the ground below the top soil is well compacted and is suitable for construction of reservoir structures.

Cutoff Trenching -

Generally, the foundations are pervious or only partially impervious due to the inherent characteristics of the underlying soil. It is therefore advisable to extend an impervious trench sufficiently deep into the foundation to insure that no seepage of water occurs through the foundation. As such, a trench is generally dug at the center line or on the upstream end of the foundation and is carefully filled with compacted impervious embankment material.

Grouting -

Grouting is generally done in rock foundations. It is intended to prevent leakage. It reduces uplift under the dam; and it consolidates seamy broken foundations making them stronger.

Cement grout usually consists of a mixture of one part cement and five to six parts water. First, a series of holes are drilled at frequent intervals in the foundation of the dam. The grout is then pumped under pressure into these holes. The thin grout usually reaches remoter seams and causes minimal disturbance to the natural formation. After sufficient thin grout has been pumped, a mixture of one part cement to two parts water, which is a thick grout, is pumped to insure proper sealing of the foundation. Where there is difficulty in sealing a seam, it is necessary to use sawdust or wood shavings along with the cement-water mixture. Hot asphalt grout has also been used to seal cavities containing running water.

Special Compaction Treatment -

There are several different methods of foundation compaction currently available for use. Some of these methods are: explosive compaction, vibroflotation and chemical/electrical treatment. These methods are generally used to consolidate and improve the characteristics of the foundation soil.

Rock Blasting/Drilling

On dam sites or reservoir sites that have a rocky foundation or canyon, certain operations will require blasting and drilling through the rocks. Construction of a tunnel through the canyon, or construction of a surface channel under rock surface will require rock blasting and/or drilling at the reservoir site.

Demolition of Existing Structures

Creation of reservoirs require the removal of all existing structures within the reservoir area.

Soil/Debris Disposal

Construction activities at a reservoir project generate large quantities of soil and debris that must be disposed of in an environmentally sound manner. A major factor of the environmental effects of reservoir projects is the availability and capacity of suitable disposal sites.

Quarrying and Stone Work

Construction of masonry dams requires large quantities of stones and rock aggregates, obtained from quarries.

Concrete Batching/Placement

A concrete batching plant is a mechanized system for producing concrete of a given strength and consistency to be transported to the site to construct structures supporting the dam. The batching plant takes measured quantities of rocks and mixes them with suitable amounts of sand and cement and water to produce the concrete needed to build masonry structures. The concrete is then transported by a suitable conveyor system to the formwork to cast concrete masonry structures. The concrete is placed in several layers and finally dried and cured.

Embankment Construction

Embankments are earth filled or rock filled structures that are built by piling up large quantities of soil or rock over a large wide base to a reasonably high depth. Earth embankments are generally wider at the base and shorter in height compared to masonry dams.

Excavation -

Large volumes of soil are needed in the construction of earth embankments. This soil is obtained by excavation of suitable borrow pits near a reservoir site.

Placing of Soil/Rocks/Gravel -

The excavated soil is transported by dump trucks and tipped off at suitable locations at the fill site. Also, the excavated material may be directly taken from the borrow pit and deposited at the filling site.

Compaction -

After the soil is placed on the base of the fill, it is compacted by various methods. One type of compaction is rolled fill, which

is produced by using sheep-foot or wobbly-wheel rollers to compact each layer of soil placed on the base of the embankment. Another type of embankment is made of hydraulic fills. In this case, the soil is hydraulically transported to the base of the embankment and allowed to settle and compact under a sufficient head of water.

Slope Protection -

Slope protection is an important feature of earth dams, embankments, and canals. One way of protecting slopes is to dump rip rap on the slopes, especially in zones where the embankment would be substantially affected by wave action of wind driven waters. Another method of slope protection is the stabilization of slopes by sodding. Still another way of protecting slopes is to provide concrete facings along the slopes vulnerable to erosion.

Dam Construction

Several alternative means of dam construction have been used, incorporating steel, masonry, concrete, and lumber in addition to the previously discussed earthen embankments. Special features of these various types of construction are described below.

Masonry Construction -

Masonry dams are of the following different types: gravity, single arch, multiple arch, arch-gravity, and buttress. Here the masonry dams have been assumed to be only those dams which use all possible types of masonry other than concrete. Construction of these structures involve transportation and placement of masonry.

Concrete Construction -

Concrete dams are of many different types, including gravity, single arch, multiple arch, arch-gravity, and buttress dams. Basically,

the concrete construction consists of preparation of formwork or shuttering, installation of steel reinforcements, transportation and placement of concrete in layers within shutterings, and drying and curing of the concrete.

Steel Construction -

Many dams have certain steel components built into them. For example, steel cranes are installed on many dams; gates and regulators are often made of steel structure; in addition, there can be many other steel structures for limited operational purposes.

In the past some steel dams have been built. However, they have been subjected to serious corrosion problems. Also, it is no longer economical to build steel dams in most instances. No steel dams are known to have been built in the past 30 years.

Lumber Construction -

Generally, dams do not have any lumber built into them. In earlier times there were some lumber dams built for storing water. These dams have proved satisfactory from the standpoint of longevity and cost of construction.

Outlet Construction

Adequate outlets must be provided in the dams to permit the water to be released for different purposes. Undersluices are used to discharge water at high head during periods of flood when the spillway runs at full capacity. Also, undersluices may be used at times when the water level is below the spillway level and downstream releases are needed. At times, intake wells are built behind the dams within the reservoir to withdraw water for purposes of water supply. Certain modern dams have fuse plugs built into the embankment. Fuse plugs may be exploded during high flood water level to discharge the water behind the dams and thus save the dam from being overtopped and destroyed by the flood waters.

Spillway Construction

Spillways are a form of overflow outlets, built into a dam, to be used during floods when the reservoir is filled above the highest storage level. Some spillways have adjustable gates at the top to regulate the flow. Generally, a spillway is designed to handle a flood with a frequency of 1,000 years. However, when actual flood flows exceed that limit, the dam is overtopped. Other outlets may be used to prevent the dam from being overtopped. If the dam is a flood control structure, it is essential that it be designed to withstand any amount of overtopping. This is very important since the failure of a flood control dam during high flood period could cause massive damage to communities downstream.

Stream Bed Protection

The release of water from the reservoir through the under-sluice or over the spillway generates tremendous amounts of power to erode the stream bed. Excessive erosion at the toe of the dam could endanger stability and hence the safety of the structure. The hydraulic jump, quickly reducing the velocity of water, is usually the most effective way of preventing erosion. Baffles or sills may also be used to dissipate energy downstream of the jump. The energy can also be dissipated on the apron by placing a sloping floor and chute blocks in the stilling pool formed on the apron.

Surface Finishing

Dams are large structures built across rivers and canyons. It is necessary that visible portions of the dam be aesthetically pleasing. The surfaces of the dam need therefore to be properly finished. The concrete dams are finely finished and the surface is suitably plastered to look pleasing in the daytime as well as at night. The earth dams are seeded with grass and maintained properly in order to be aesthetically pleasing and to prevent erosion as a result of rain, wind, and snow.

Landscaping

Development of a suitable aesthetically pleasing landscape at and around a reservoir site is an important feature of water resources projects. This can be achieved by seeding all man-made fills, excavated and quarried sites, and also slopes eroded by natural forces. Intelligent planning of borrow pits and fill sites can create excellent physical arrangements for aesthetically pleasing landscapes around reservoir sites.

OPERATION AND MAINTENANCE

After the project has been partially or completely built, it should be operated in accordance with the approved design specifications and operating procedures to produce the specified project output. Maintenance activities must also be undertaken to ensure that the safety, stability, and environmental desirability of the project is maintained.

Operation activities and output characteristics will have a variety of impacts. Some impacts will be general to all large reservoirs. Others will depend on how the specific project purpose modifies reservoir operations, primarily timing, duration, and magnitude of water releases and reservoir water levels. General reservoir operation and maintenance activities include:

- Reservoir filling
- Spillway operation
- Outlet operation
- Dredging
- Foundation drainage
- Aeration
- Herbicide treatment
- Mechanical plant removal
- Evaporation control
- Repairs of defects, leaks, and weaknesses

● Function-related activities associated with reservoirs including:

- recreation
- power generation
- flood control
- domestic water supply
- agricultural water supply
- multipurpose projects.*

Reservoir operation and maintenance activities can cause a variety of water quality, ecological, aesthetic, and socioeconomic impacts of varying durations and degrees. Water quality impacts result primarily from the alteration of a free-flowing stream to a standing body of water. Water quality impacts can be associated with two different phases of reservoir operation. The first is the transition phase involving filling of the reservoir and the first several years of operation. The second phase involves the water quality characteristics of the reservoir after transitional types of water quality impacts have subsided.

In the first phase, decomposition of any remaining organic material on the project site will alter the incoming stream water quality, due to biological oxygen demand and enrichment of the water in the decomposition process. Floating material and the initial turbidity level also may be higher during this first phase than that of the incoming waters. These general water quality alterations will be reflected to a certain extent in the outflow of the reservoir and in downstream water quality.

The most important water quality changes, however, are related to the effect of impounding free-flowing water. One of the primary factors here is the degree to which impoundment results in thermal stratification of the reservoir. Thermal stratification will create a warmer layer of water overlying a lower colder strata during warm weather. The opposite pattern generally holds during the winter.

* Most large reservoirs will involve multiple purposes and this is probably the most typical situation that the impact statement reviewer will face.

The effect of this stratification is most pronounced in the summer when the colder bottom layers tend to be void of oxygen. Major implications of this relationship are complex and are discussed in detail in Section III of this report. In general, release of oxygen-deficient cold waters from the bottom layers of the reservoir in summer will alter downstream preproject water quality characteristics just as release of warmer waters from the surface layers of the reservoir will alter the preproject downstream water quality.

Other water quality impacts that may result from operation include an increase in clarity as fine sediments settle out of the standing water, alterations in downstream flow regime due to timing and frequency of releases from the reservoir, and water level fluctuations within the reservoir itself.

Ecological impacts due to operation will relate to the above physical/chemical changes. Fundamental among these will be downstream water level fluctuations at critical periods in the life cycle of aquatic organisms and similar water level fluctuations within the reservoir itself. Downstream changes in physical/chemical water quality may also alter the nature of the aquatic ecosystem. In this case temperature is a primary factor of concern. Problems of oxygen-deficient water or water that is super saturated with nitrogen also play an important role in downstream ecosystems as does the physical blocking of the stream for migration for certain species of fish. Impacts on terrestrial ecology from operation of the reservoir will be very site-specific but relate primarily to elimination of terrestrial habitats due to flooding and to the interface of the terrestrial ecosystem with the ecosystem in the stream reach below the reservoir.

Most aesthetic impacts associated with reservoir operation will be related to the amenity conditions such as noise and odor problems. Odor may occur under certain conditions of algal growth or anaerobic phases of decomposition. Noise will relate to secondary developments around the reservoir and traffic generation caused by socioeconomic changes.

Socioeconomic impacts are a direct function of the reservoir purpose, its size, and its proximity to urban populations. The most

significant consideration from an operational point of view is the extent to which project operational characteristics induce various secondary developments. Important among these are second home development, recreational use, and industrial location due to increased water and power supplies. These developments, along with those associated with the specific project purpose (for example, irrigation) can be expected to change regional income and income distribution, create new demands for public services and new sources of public revenue, and cause changes in existing social activity patterns and life styles.

Specific operations and maintenance activities are defined and described below.

Reservoir Filling

The first filling of the reservoir is an important event in the life of the project. Many difficult environmental and safety problems may rise during filling. It takes about 5 years before the new reservoir environment approaches stability. The first filling of the reservoir should be carefully and cautiously handled and monitored. Also, during the first 5 years, the reservoir filling operation should be given substantial attention to determine the types of erosion problems that might develop, and potential seepage, leakage, and piping problems that are likely to develop in the dam or along the natural reservoir embankment. The transportation of silt from upstream disturbed areas into the reservoir should also be monitored and abated.

Spillway Operation

The operating procedures of the spillway are an important aspect of the reservoir environment. They determine the highest water level upstream of the spillway as well as the fluctuation of water downstream.

Outlet Operation

The outlet operation greatly depends on the purpose for which the reservoir has been built. Uniform releases are generally made from a water supply reservoir. Periodic releases are made from power dams as well as agricultural reservoirs. The flow rate varies daily in the case of power reservoirs, whereas in the case of agricultural reservoirs it may vary seasonally.

Dredging

The dredging of reservoirs, channels, and canals is an important activity in many water resources projects. A reservoir that is being rapidly silted up must be dredged to prevent its losing effective storage capacity. Channels for navigation must be dredged regularly to increase the effectiveness of their use. Channelization is done in sluggish streams to enhance the rate of flow, thereby preventing flood damage in the vicinity of the stream. Also, silt transported with irrigation water from the reservoir can fill up deep irrigation canals unless periodically dredged.

Foundation Drainage

Foundation drainage is an important feature of a water resource project. Creation of reservoirs and canals as components of many water resource projects results in water logging due to the lack of proper drainage in areas that have impervious or semi-impervious soils. Water logging may create many serious problems, including breeding of mosquitoes, flies, and other insects and disease microorganisms. Suitable drainage will therefore be designed in the dam foundation as well as in the vicinity of reservoirs and canals where water logging is likely to occur.

Aeration

Reservoirs are aerated to prevent dissolved oxygen deficiency problems that may result from reservoir stratification.

Herbicide Treatment

Many different kinds of undesirable vegetation can grow on the sides and shallow bottoms of reservoirs. The growth of these undesirable organisms can be controlled by using specific types of herbicides. However, the use of herbicides in an excess amount can cause serious chemical pollution of water, thereby endangering aquatic organisms and water quality.

Mechanical Plant Removal

The growth of plants in the reservoirs can create serious water quality problems as well as reduce the capacity of reservoirs. Therefore, to maintain sufficient capacity within these reservoirs it may be necessary to use mechanical devices for plant removal from the reservoir bottom.

Evaporation Control

In warm arid regions, the reservoir is subjected to a high rate of evaporation loss from its surface. Also, certain categories of plants cause serious evapotranspiration losses from reservoirs. Such evaporation and evapotranspiration losses can be abated by various methods. Certain organic films or monolayers of cetyl alcohol, stearyl alcohol, etc., can be sprayed over the water surface to prevent excessive evaporation. Also, the use of certain chemicals to poison these highly transpiring plants around a reservoir can effectively abate high evapotranspiration losses from reservoirs.

Repairs of Defects, Leaks, and Weaknesses

Dams and reservoirs are always subjected to significant stress caused by natural changes in the environment. These stresses may cause major defects in the structure of the reservoir. They may lead to serious leaks and weaknesses in the structure of dams and embankments. These deficiencies can have serious implications for the aquatic environment. Timely repairs are needed to guard against potential damages to the environment.

Function-Related Activities

The magnitude, frequency, and duration of operational impacts will often be related to the purpose of a specific reservoir project. While reservoirs are usually designed for multipurpose outputs, description of individual functions and their relation to operational impacts can be useful in understanding the impact generation process. Each of several individual functions is discussed briefly below.

Recreation -

Permanent recreation facilities and stable recreation use of a reservoir requires the maintenance of a minimum elevation pool during the recreation season. This requirement, if dominant, will tend to regularize flows during the recreation season. Depending on the level of the reservoir at the end of the winter, high spring flows will normally be withheld, reducing downstream flow. Again, depending on the rules governing downstream releases and pool elevation during the recreation season, excess runoff will probably be withheld. This will further regularize downstream flows. The ecological impact of regularization relates to the life cycle of various aquatic species, particularly those that require high spring flows for access to spawning areas. Other impacts associated with recreation reservoirs relate to recreation use and recreation facilities and second home development. Heavy recreation use (power boats in particular) will create water quality problems. Extensive recreational development may create water quality problems if septic tanks or sewage facilities are inadequate. Traffic congestion may also be a problem during periods of peak use.

Power Generation -

Falling water is a resource for generating electricity. A run-of-river plant uses only unregulated river discharges and is practical only on streams with appreciable dry-weather flow. A pondage plant, on

the other hand, retains the night-time discharges for use during the peak hour power demand of the next day. Still another category is the seasonal storage plant that retains the wet-season flood flows for use during the subsequent dry periods. The cyclic storage plant has the capacity to store water lasting several years during extended dry periods.

Another facet of power production is pumped storage. A pumped storage development is a reservoir facility intended for peak-load power generation. In the United States and many other industrialized countries, the operations of nuclear power stations with high output ratings have frequently been tied to large pumped-storage facilities. Also, there has been a tendency to develop storage power stations of an economic combination of large dams and pump-storage operations. This arrangement very effectively increases the firm peaking power capacity of a generating system. However, pumped-storage systems without natural inflow continue to be predominant at this time. In principle, the pump-storage facility permits the operation of major power stations at a rating higher than the off-peak demand. The excess energy generated during off-peak hours is used to pump water to an upper reservoir for storage. During the peak hours, the pumped-storage reservoir releases the off-peak stored water to generate additional power needed above the output rating of the power station.

A hydroelectric power project stores water in a reservoir and allows it to pass through trashracks, penstocks, and then through the turbines. The energy of the falling water is thus converted into rotating shaft energy, which in turn is transformed into electrical energy by generators. Downstream of the power plant there is generally an afterbay to even out the discharge pattern of evening peaks and early morning low flows. The general effect on flow is to cause increased fluctuations, either on a daily basis in the case of peaking facilities, or to increase fluctuation seasonally in the case of base load facilities.

Increased water level fluctuations, either daily or seasonally, have major implications for downstream and reservoir aquatic ecology. These are described in detail in Section IV of this report. In general, change in natural patterns of downstream water level fluctuation can be in conflict with the spawning, nursery, and feeding requirements of

various fish species. Similar conflicts will also limit the productivity of the reservoir itself, if water level fluctuations are significant at critical times of the year. Other specific impacts that can be linked to power projects include aesthetic effects such as conspicuous "bath tub rings" (the draw down zone), power transmission lines, and potential industrial development or expansion.

Flood Control

A flood control reservoir has the capacity of containing high flood flows up to a given maximum discharge. The retarding structures and reservoirs store peak flows in order to reduce flood damage downstream. In addition, channel improvements may be made to enhance the flood carrying capacity of rivers. Also, levees keep the water away from developed areas. The floodways and bypasses divert flood flows from the main stream around developed areas of a city and prevent flood damage. The major influence of flood control projects is to create a more regular flow during most of the year, which will have environmental impacts similar to those discussed for recreation reservoirs. A single purpose flood control reservoir will be operated differently, however. Extensive capacity will generally be maintained to accommodate sudden, large discharges. In the extreme, this operational feature will result in an unstable aquatic habitat in the reservoir itself. Regularization of downstream flows may or may not be beneficial to the aquatic habitat, depending on pre-project conditions.

Other types of impacts relate to the downstream land development incentives created by flood protection. Urban encroachment on the flood plain following construction of the reservoir will result in terrestrial habitat losses over and beyond those caused by the reservoir itself and may lead to catastrophic losses from a truly major flood.

Domestic Water Supply -

Water supply projects are intended to supply adequate quantity and quality of water for municipal, commercial, and industrial operations.

Operationally, water supply reservoirs tend to regularize flow since the project is designed to provide a steady output of potable water. The effects of regularization would be similar to those described for recreation reservoirs. For a single purpose domestic water supply project, however, pollution would be less of a problem due to the absence of recreational use.

Agricultural Water Supply -

Single purpose irrigation projects involve storage and transmission of water to extend the area of arable land or to improve the productivity of existing cultivated land. Basically, these projects consist of reservoirs that store off-season flows for use during the irrigation season, and a system of canals that transport water to lands that need water for agriculture. Irrigation projects tend to smooth water flow, storing high flows in the spring and releasing them during dry summer months. Water levels in the reservoir will tend to have a wider variability than those in single purpose domestic water supply or recreation reservoirs. This is due to the seasonal drawdown for crop water consumption requirements. Seasonal variation in water levels may result in lower than maximum potential productivity for the reservoir. Regularization of downstream flows may have either a beneficial or adverse effect on aquatic ecology.

The irrigation water, after passing through permeable soils, is capable of returning to the same river at some point downstream. The chlorides, nitrates, and other salts present in the soil may be dissolved by the irrigation water as it passes through these soils. At the point where these agricultural flows return to the river they may have a high degree of salinity. As such, the irrigation return flows can be the cause of serious water quality problems in many areas. Also, the operation of canals can have major impacts on the environment of a given region. Excessive water logging can create serious insect and bacterial damage to nearby areas.

Multipurpose Projects -

Most major water resource projects are built with multiple purposes in mind. For instance, a reservoir may be built to control floods during flood season, as well as provide water supply during most parts of the year. It may be used for irrigation as well as power generation and waste water dilution. In addition, most large reservoir projects built today include provisions for recreation. The impacts associated with multipurpose reservoirs cover the spectrum of general impacts discussed previously as well as those that are specific to the dominant reservoir function. Detailed discussion of these impacts is the subject of the next two sections of this report.

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SECTION III

WATER QUALITY IMPACTS RESULTING FROM RESERVOIR CONSTRUCTION

INTRODUCTION

The most fundamental changes produced by reservoir construction include changes in physical and chemical characteristics of the water itself. These water quality changes, in turn, trigger further changes in the ecology, aesthetic quality, and ultimately in the human use of the reservoir region.

The major water quality impacts of reservoir construction can be grouped into three main areas: temperature impacts, dissolved oxygen impacts, and impacts on chemical constituents of the water. Of these three areas, temperature impacts are the most pervasive with other changes driven by or closely linked to temperature. The level of biological activity, for example, (as measured by gross productivity) doubles for every 10 degree Centigrade increase in water temperature, creating a corresponding increase in oxygen demand. Dissolved oxygen solubility decreases when temperature increases.

The activity and fate of chemical constituents such as nutrients and toxic chemicals such as pesticides are also closely interwoven into this web of interactions. The reservoir itself acts as a nutrient and chemical trap, incorporating chemical constituents into the bottom sediments in stabilized forms. When the reservoir becomes thermally stratified, however, these chemical constituents may be released from the sediments due to anaerobic decomposition. Thus, water quality downstream from the reservoir may fluctuate widely with time; from the free flowing stream condition to a state of chemical impoverishment to chemical enrichment.

The above examples illustrate the important and complex interactions that occur between water quality characteristics and between water quality and other aspects of the reservoir system. In some cases, these interactions are sufficiently well understood to permit the prediction of water quality characteristics anticipated after reservoir construction via mathematical formulae or simulation models. This section reviews the most important of

the analytical models for predicting water temperature, dissolved oxygen, and chemical constituents. In each case, major reservoir influences on the impact area are described, then tools for predicting in-reservoir conditions are described and compared, and finally, downstream impacts in the water quality impact area are considered. These three sections on major water quality impact areas are preceded by a discussion of factors controlling reservoir water quality, and followed by a list of references for more in depth discussions.

GENERAL CONTROLLING FACTORS

Changes in the quality of water due to impoundment depend on many variable characteristics. Some parameters are related to natural processes while others are related to reservoir design and management. The major stresses which seem to control the quality of water are:

- (a) The quality of the inflowing water
- (b) Climatic controls, including precipitation, temperature, insolation, wind, and evaporation
- (c) Inorganic chemical reactions, including chemical precipitation, complex formation, and oxidation-reduction reactions
- (d) Morphometric controls, such as the size, shape, and depth of the impoundment
- (e) Biological controls with regard to effects of living organisms upon organic and inorganic materials
- (f) Management controls, including factors manipulated by man to regulate conditions within the reservoir or downstream from it, such as retention time. (Love and Slack, 1963).

Brief descriptions of these characteristics follow (Burdick and Parker, 1971):

The quality of the inflow is of obvious importance in controlling the water quality in an impoundment. Average values of the various water quality parameters, as well as their variation with time, are of interest.

In approaching prediction or simulation of reservoir water quality, the quality characteristics of the inflow probably provide the most likely starting point and are a baseline condition from which quality changes may be measured.

Climatic controls, including precipitation, temperature, wind, evaporation, and solar radiation, exert an influence upon both the inflow quality and the processes which occur in the reservoir. Precipitation, by controlling the inflow rate, affects the residence time of the water in the reservoir and the dilution and mixing properties of the reservoir. Temperature is of great importance physically, chemically, and biologically. Water density, viscosity, vapor pressure, surface tension, and the solubility and diffusion of gases are temperature dependent, as are the rate and extent of chemical and biochemical reactions. The temperature effect on water density is of major importance. It causes the phenomena of thermal stratification, which presages many changes of reservoir water quality. Wind influences evaporation, gas exchange, and mixing. Evaporation tends to produce increases in concentrations of dissolved materials and may represent a significant water loss in many reservoirs. Solar radiation affects temperature and photosynthesis.

Inorganic chemical reactions include the actual mechanisms by which many important quality changes occur. Included are solution, precipitation, complex formation, and oxidation-reduction reactions.

Morphometric controls account for many differences in the behavior of different impoundments. Length, depth, shape, and other parameters descriptive of the physical system are important in generalizing and comparing reservoir systems.

Biological controls are closely interrelated with inorganic chemical reactions as the mechanisms of quality changes. The change may arise from extraction of materials from the water, addition of materials to the water, or promotion of oxidation-reduction reactions.

Management controls include any management practices in the drainage basin and any operational practices of the dam and reservoir. Reservoir outflow rate, water surface level control, reservoir site preparation, and other such controls exert various influences upon the water quality in the reservoir, and downstream from it.

It is recognized that water quality may be improved or degraded by impoundment. Some of the more significant beneficial and detrimental effects of impoundment have been reported (Love, 1961). Important beneficial effects of impoundment on water quality include:

- (a) Reduction of turbidity, silica, color (in certain reservoirs), and coliform bacteria
- (b) Evening out of sharp variations in dissolved minerals hardness, pH, and alkalinity
- (c) Reductions in temperature which sometimes benefit fish life
- (d) Entrapment of sediment, and
- (e) Storage of water for release in dry periods for the dilution of polluted waters.

In addition, impoundment also has certain undesirable effects, such as:

- (a) Increased growth of algae, which may give rise to tastes and odors
- (b) Reduction in dissolved oxygen in the deeper parts of the reservoir
- (c) Increase in carbon dioxide and frequently iron, manganese, and alkalinity, especially near the bottom
- (d) Increases in dissolved solids and hardness as a result of evaporation and dissolution of rock materials, and
- (e) Reductions in temperature, which although sometimes beneficial, may also be detrimental to fish life.

The prediction of impacts in these areas is a complex problem. The complexity comes from the interrelationship of the parameters and from the fact that the changes in the water quality occur not only at the reservoir itself, but also downstream from the reservoir, and, in nearby estuaries. In general, approaches to predicting the impacts in various locations are essentially the same. However, the specific models developed at each location differ from one another due to differing physical, chemical, and biological processes taking place at various locations. Most models are

based on processes of mass, heat, or momentum balance, but because of the assumptions and initial conditions used, solutions differ, thus the resultant different models for the locations. For example, most reservoirs of reasonable depth in the United States will stratify during the summer. This situation presents difficult problems in the analysis of the temporal and spatial distribution of temperature and dissolved oxygen. In contrast, the temporal and spatial distribution of the impact areas in flowing streams (downstream) or uniformly mixed reservoirs, are relatively simple to characterize and quantify, because of their homogeneity. In the estuary a different situation exists. Fluid motion is a complex interrelationship of unsteady, nonuniform free surface flow due to tidal motion and fresh water flow from upland rivers or impounded water low in DO and temperature. The intrusion of the dense saline water from the sea will have an important influence on the chemistry and biota of the estuary.

For convenience in this discussion, the reservoir impact on the abiotic water quality parameters may be grouped into the following impact areas: temperature, dissolved oxygen (DO), and chemical. These impact areas are influenced by the abiotic and biotic parameters. It is important to recognize that neither these impact areas nor their constituent parameters can be separated into isolated compartments. They are characterized by a high degree of interrelationship. In the following sections, the impact areas as affected by reservoirs at the various locations are described, along with a selected number of modeling and prediction techniques.

TEMPERATURE IMPACT AREA

Major Reservoir Influences on the Temperature Impact Area

Temperature is the single most important physical parameter of water quality. The temperature affects other physical properties of the water such as density, viscosity, vapor pressure, surface tension, and solubility of gases and solids. Table 1 details the change in these properties with change in temperature. Temperature also controls the

TABLE 1. WATER PROPERTIES AS A FUNCTION OF TEMPERATURE
(From Parker & Krenkel, 1969)

Temperature °C	Vapor Pressure mm.Hg	Viscosity Centipoise	Density gm/ml	Surface Tension Dynes/cm.	Oxygen Solubility mg/l	Oxygen Diffusivity cm ² /sec
0	4.579	1.787	0.99984	75.6	14.6	
5	6.543	1.519	0.99997	74.9	12.8	
10	9.209	1.307	0.99970	74.2	11.3	15.7
15	12.788	1.139	0.99910	73.5	10.2	18.3
20	17.535	1.002	0.99820	72.8	9.2	20.9
25	23.756	0.890	0.99704	72.0	8.4	23.7
30	31.824	0.793	0.99565	71.2	7.6	27.4
35	42.175	0.719	0.99406		7.1	
40	55.324	0.653	0.99224	69.6	6.6	

biologic processes occurring within the water. Furthermore, temperature is an important factor in determining its use for drinking, cooling, irrigation, or recreational purposes. Temperature, therefore, is of great importance physically, chemically, biologically, and in the intended use of the impounded water.

The construction of a reservoir on a free-flowing stream frequently results in two important changes relative to water temperature. First, a seasonal pattern of thermal stratification may develop in the reservoir. During the summer season, a warm upper layer may be separated from a distinctly colder bottom layer by intermediate transition zones. Such stratification is of major importance because it creates two distinctly different and physically separated environments for biological and physical/chemical activity. In contrast, the original free-flowing stream was a single homogeneous environment. The second major water temperature change resulting from impoundment relates to the water temperature per se. Because water is held in the reservoir and downstream flow rate is reduced, surface waters receive a greater amount of direct solar heating. Thus, they are generally warmer than the original stream temperature. Bottom layers, in contrast, are physically cut off from such solar heating during periods of summer and winter stratification. Therefore, bottom water temperatures are frequently cooler than the previous free flowing stream temperature.

These two types of temperature related reservoir impacts, stratification and absolute temperature changes, are of major significance because of their effect on biological and chemical activity within the water body and their interaction with other water quality factors. The original stream plant and animal community may be replaced by two entirely new communities following reservoir construction; one occupying the warm water zone and the second occupying the cold water zone. Such species changes may be of direct importance, as when an original trout population is replaced following reservoir construction by species more adapted to warm water conditions such as bass and blue gill. Reservoir temperature changes will alter not only the specific plant and animal species present but also the general level of biological activity in the waters. Primary productivity of algae and microorganisms in the warmer upper layers will be increased by impoundment

while the productivity of the colder lower layer may be reduced. Temperature changes also will have an important impact on the chemical solubility of the water. Most importantly, the capacity of water to retain dissolved oxygen decreases as water temperature rises.

Though the temperature changes and resulting impacts discussed are the result of a complex interaction of factors, some general guidelines may be suggested for identifying those conditions under which temperature related impacts may be expected to be most severe. Reservoir depth is an obvious important factor. Only relatively deep reservoirs (20 to 30 feet or more) will stratify. The nature of the inflow water is another important factor. Potentially, undesirable temperature impacts will be more severe when large quantities of warm water are introduced to the reservoir due either to large summer inflows or upstream heating of the water through man's activities such as power plant or sewage plant operations. When such warmer inflows also possess high salt concentrations due to the acid mine drainage, irrigation return flow, or soil conditions in the runoff area, impacts may be particularly severe. The severity of temperature related problems is also a function of some outflow characteristics. For example, when the outflow is taken consistently from the bottom layer of the reservoir the retention time of water in the upper layers of the reservoir is greatly increased and thus water temperatures there are increased by solar heating. Similarly, temperature related problems may result when large withdrawals from the reservoir are made during the spring and fall turnover period but relatively small withdrawals are made during the summer and winter stratification periods.

Thermal stratification, a layering of water in the reservoir, is a phenomenon induced by differences in temperature and thus density. In shallow reservoirs where the isotherms tend to be tilted in the downstream direction, stratification is relatively weak, and variation with depth of other physical parameters is insignificant. This is a condition characteristic of uniform, free flowing streams.

In deep reservoirs (30 feet or more) having a storage volume which is large compared to the annual through flow, the isotherms are horizontal during most of the year and strong stratification may develop during certain seasons. For a well stratified reservoir, three distinct zones are developed

with depth in the reservoir of the epilimnion (surface), the thermocline (middle), and the hypolimnion (bottom). Thermal stratification causes nonhomogeneous mixing of the reservoir which affects the extent of dilution and mixing of the inflow waters. The main factors affecting the thermal characteristics of a reservoir are its depth and the climatic regime of the region. The temperature cycle can be summarized as follows:

- Winter: Reservoir isothermal with depth. Water at maximum density throughout; deep vertical motions established by small wind forces at the surface.
- Spring: Warming of surface. Epilimnion and upper layers become uniform in temperature and relatively warm. Water circulates here and is turbulent. Hypolimnion (lower layer) remains undisturbed and fairly cold. Thermocline (plane at which temperature decreases most rapidly with depth; also a zone of discontinuity between water masses) subject to large vertical motions due to wind motions.
- Autumn: Epilimnion cools and increases in thickness. Thermocline disappears; lake becomes isothermal.
- Winter: Inverse of stratification is sometimes observed; in large-deep lakes heat storage is great and ice formation can be nil. (Anderson and Pritchard, 1951).

The classical pattern of thermal stratification in lakes or reservoirs is shown in Figures 1 and 2. Of particular interest are the patterns of water circulation and salinity distribution in Lake Mead. These patterns are controlled largely by density flows; which vary markedly with seasons of the year. Three kinds of density flows are described--overflows, interflows, and underflows (Love, 1961).

An overflow takes place when inflowing stream water spreads over the surface of the reservoir. The overflow may travel for a considerable distance and then mix with water near the surface by action of wind and waves.

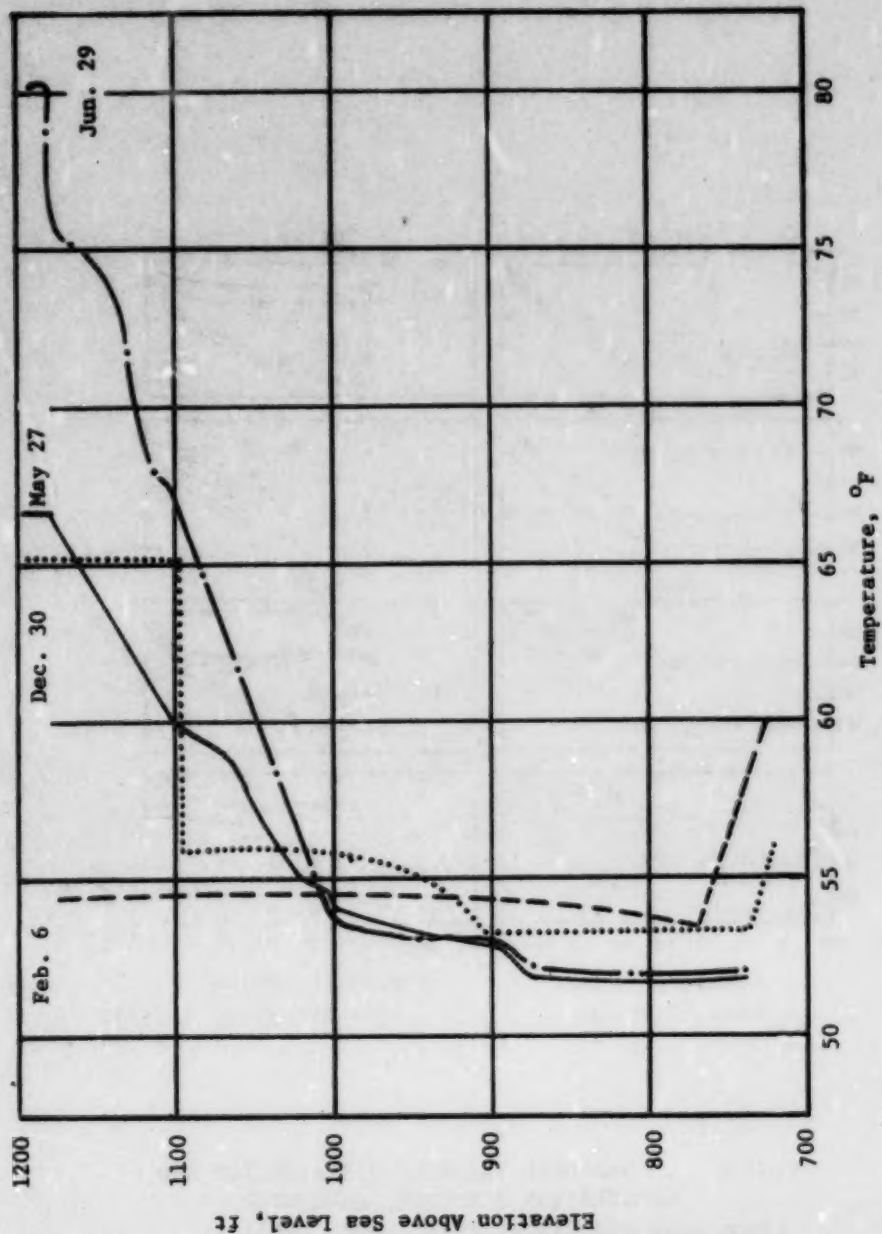


FIGURE 1. SEASONAL VARIATIONS IN TEMPERATURE GRADIENTS, LAKE MEAD, 1948
(From Love and Slack, 1973; Love, 1961)

(Note: These data represent conditions at the Hoover Dam intake towers, comparable to river mile 355 on Figure 2, page 38.)

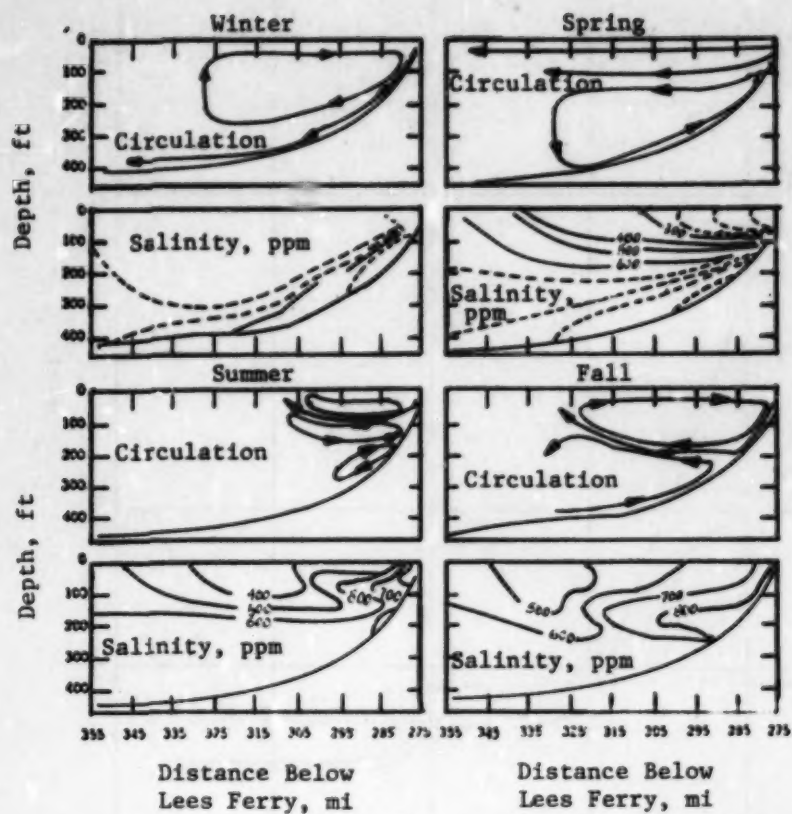


FIGURE 2. SEASONAL SALINITY DISTRIBUTION AND CIRCULATION PATTERNS, LAKE MEAD
(From Love and Slack, 1973; Love, 1961)

An interflow takes place when the density of the inflowing water is greater than that of water on the surface of the reservoir but less than that of deep water. The inflowing water sinks to its own density level in the reservoir and then spreads out laterally downstream.

An underflow takes place when the density of the inflowing water is greater than that of the water at any level in the reservoir. The inflowing water sinks to the reservoir bottom and travels downstream at or near the bottom, usually along the old river channel.

Figure 2 shows seasonal salinity distribution and circulation patterns in Lake Mead. In winter there is almost complete vertical mixing of the water, and there is a simple circulation pattern. The inflowing water is colder and more dense than the lake water and flows downstream as an underflow. This pattern of flow would be expected to occur when the temperature distribution is nearly uniform throughout most of the water column. (See Figure 1, Feb. 6)

The greatest quantity of runoff occurs in the spring when the flow is low in dissolved solids and high in suspended solids. At this time the temperature of inflowing water is about the same as that of the surface of the lake and the sediment settles out rather quickly. Thus, the inflowing water proceeds into the lake as an overflow. Stratification of the lake waters takes place with a vertical gradient of temperature and salinity. The flow along the surface sets up a cellular circulation below 150 ft., which causes an upstream flow along the bottom.

In the summer the inflow decreases in volume and increases in salinity. The downstream travel of the river water takes place as an interflow at a depth of about 80 ft.

In the fall, the decrease in the temperature of the inflow causes greater sinking of the river water along the bottom as an underflow until it comes in contact with heavier water and then spreads out horizontally as an interflow.

Techniques or Modes for Predicting Temperature in Reservoirs

The first step in the development of a temperature model is to consider all factors involved in the exchange of heat between the water body

and its environment. The degree of correlation of the predicted with the measured data depends on how closely the model approximates the actual physical situation modeled. Assumptions are made for specific situations to give models varying in correlation and complexity. In general the simplest models have poor correlation with the actual since all the sources and sinks of heat to the medium are usually not accounted for, while the more complex models have better correlation because of their inclusiveness. In the following paragraphs, major characteristics of a selected number of simple and complex models for predicting temperature are described. These models are summarized in Table 2.

Turbulent Diffusion Models -

Turbulent diffusion models assume that the entire incoming solar radiation is absorbed at the surface of the water. Several models in this category will be discussed.

The simplest model in this category is a simple second-order differential equation with constant vertical thermal eddy diffusivity (Burdick and Parker, 1971):

$$\frac{\partial T}{\partial t} = Dz \frac{\partial^2 T}{\partial z^2} \text{ where} \quad (1)$$

T = temperature (C)

t = time (t)

z = vertical coordinate measured downward from the water surface (L)

Dz = vertical thermal eddy diffusivity (L^2/t).

Output of this model is the time-depth distribution of temperature down the water column.

The primary inputs are:

- The initial and boundary conditions
- The vertical-turbulent diffusion coefficient
- Surface water temperature

TABLE 2. SELECTED TEMPERATURE MODELS

Model Type	Major Model Assumptions	Parameters Measured	Reservoir Model Correlation of Predicted with Measured	Simulation Method	Reference
TYPE I (Turbulent Diffusion)	1. Horizontal temperature homogeneity 2. Inflow and outflow temperatures input and output negligible 3. Coefficient of vertical turbulent diffusion constant with depth 4. Change of area with depth negligible 5. Coefficient of thermal conductivity constant 6. Equilibrium temperature variation is a sine function	1. Wind speed 2. Air temperature 3. Air humidity 4. Net incoming radiation 5. Surface water temperature 6. Equilibrium temperature 7. Heat exchange coefficient 8. Vertical turbulent diffusion coefficient	Priest Reservoir Very Poor Correlation	Short Computer Simulation	Burdick and Fether, 1971
TYPE II (Turbulent Diffusion)	(Same assumptions as 1 through 4 above) 5. Coefficient of thermal exchange is a cosine function 6. Change of area with depth is an exponential function 7. Coefficient of thermal exchange is a cosine function	1 through 8	Priest Reservoir Poor Correlation	Short Computer Simulation	Burdick and Fether, 1971
TYPE III (Turbulent Diffusion)	(Same assumptions as 1 and 3 above) 2. Inflow and outflow are advective heat sources and sinks 4. Change of area with depth is an exponential function 5. Coefficient of thermal exchange is a cosine function	1 through 8 Change of area with depth	Priest Reservoir Fair Correlation	Short Computer Simulation	Burdick and Fether, 1971
General Model (Turbulent)	(Same assumptions as 1, 4, and 5) 2. Inflow and outflow are advective heat sources and sinks 3. Coefficient of vertical turbulent diffusion varies with depth and friction velocity 6. Equilibrium temperature variation a sine function	1 through 8 Change of area with depth Inflow and outflow temperature	Priest Reservoir Fair-Good Correlation	Short Computer Simulation	Burdick and Fether, 1971
Internal Absorption	1. Non-homogeneity of horizontal temperature profile 2. Net shortwave energy distribution beneath the water surface a decaying exponential function 3. Coefficient of turbulent diffusion not constant 4. Change of area with depth significant	1 through 7 Vertical turbulent diffusion coefficient measurement Inflow and outflow advective temperature Hydrologic, meteorologic, climatologic conditions Cloudiness, DB-temperature, barometric pressure, wind velocity	Coyage Lake Good Correlation	Numerical Analysis by Computer	Sundaram, et al., 1971
RTT Model	1. Thermal gradient exists in vertical direction—horizontal homogeneity 2. Sides and bottom of the reservoir insulated 3. Density, specific heat, coefficient of molecular diffusivity constant 4. Solar radiation is absorbed both at the water surface as well as in the water body 5. No "entrance" complications due to density differences 6. Withdrawal can take place from several levels, singly or concurrently	1. Solar radiation 2. Atmospheric radiation 3. Air temperature 4. Relative humidity 5. Wind speed 6. Streamflow rate 7. Streamflow temperature	Pontaux Reservoir Good Correlation	Explicit Numerical Analysis by Electronic Computer	Orlob and Salas, 1968; Water Resources Engineers, Inc., 1969; Corps of Engineers, 1970; Becca, et al., 1971 Ryan and Karlman, 1971; Mohr and Karlman, 1966; Roberts, et al., 1972

- Net rate of surface heat exchange
- Temperature exchange rate below the water surface.

The general assumptions of this model are:

- Net rate of surface heat exchange is a linear function of the thermal exchange coefficient, and an equilibrium temperature. Both the thermal exchange coefficient and equilibrium-temperature are expressed as functions of the wind speed, air temperature and humidity, and net incoming radiation (Richardson, 1920; Ifeadi, December 5, 1973; Ryan and Harleman, April, 1971; Water Resources Engineers, Inc., 1969)
- The temperature exchange below the water surface is negligible
- Any horizontal plane is homogeneous with respect to temperature.

Equation 1 may be slightly modified with specific assumptions to give more specific models (Burdick and Parker, 1971): TIDEP I, TIDEP II, and TIDEP III.

TIDEP I. The model is as given in equation 1 with the following additional assumptions:

- Inflow and outflow are negligible
- The change of area with depth is small
- Variations of thermal exchange coefficient and equilibrium temperature with time are cosine functions.

Simulation of Priest Reservoir showed this model to be unsatisfactory. It is therefore not applicable for reservoirs whose inflows and outflows will affect the temperature of the system.

TIDEP II. This model is the same as TIDEP I, except the influence of a varying reservoir geometry with depth is included in the model. For Priest Reservoir which was modeled, the variation of the area with respect to depth was assumed as an exponential function. The correlation showed slight improvement over TIDEP I, but was still not satisfactory, showing that the model may not be applicable in reservoirs with significant temperature inflows and outflows.

TIDEP III. This model is the same as TIDEP II but evaluates an additional parameter; namely, the effects of inflow and outflow temperature (advection parameter). The study of Priest Reservoir showed a significant improvement over TIDEP II, showing the importance of inflows and outflows as significant sources and sinks of heat in the reservoir.

Cornell Model. This model is also based on the turbulent diffusion model but with variable vertical turbulent diffusion coefficient which is given as a function of Richardson number. The general second-order differential equation is (Sundaram, et. al., February, 1971):

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(K_H \frac{\partial T}{\partial z} \right) \quad (2)$$

where

- T = temperature (C)
- t = time (t)
- z = vertical coordinate, measured downwards (L)
- K_H = the eddy diffusivity for the vertical transport of heat
 - = $K_{Ho} (1 + \sigma_1 R_1)^{-1}$ (Schlichting, 1955)
- K_{Ho} = the eddy diffusivity under identical environmental conditions, but on the absence of stratification
- σ_1 = empirical constant
- R_1 = Richardson number (Richardson, 1920; Pritchard, 1960)
 - = $-\alpha_v g z^2 \frac{\frac{\partial T}{\partial z}}{w_*^2}$
- w_* = $\sqrt{s/\rho}$ the friction velocity
- s = surface shear stress induced by wind
- ρ = density of water
- α_v = coefficient of volumetric expansion of water
- g = acceleration due to gravity.

Output of this model is the time-depth distribution of temperature down the water column in the reservoir.

The general assumptions of the model are:

- Net rate of surface heat exchange is a linear function of thermal exchange coefficient and the equilibrium temperatures
- Vertical diffusion coefficient is variable, a function of the Richardson number.
- Horizontal plane is homogeneous with respect to temperature
- Temperature exchange below the water surface assumed negligible.

The primary inputs are:

- The initial and boundary conditions
- The eddy diffusivity, based upon
 - The temperature of the reservoir at maximum spring homothermy
 - Net rate of surface heat exchange.

Specifically, these primary inputs are:

- The variation of the equilibrium temperature over the water body of the reservoir. The quantities depend on the climatic conditions above the water body, and methods of determination are discussed elsewhere (Sundaram, et.al., November, 1969).
- The heat exchange coefficient. This is also a function of environmental conditions above the water, and the method of determination is discussed elsewhere (Sundaram, et.al., November, 1969).
- The annual variation of the average wind speeds above the water body. This is used in the calculation of the Richardson number (Munk and Anderson, 1948).

On the study done with Cayuga Lake (Sundaram, et.al., February, 1971), the model gave an excellent correlation with observed data, thus it

was recommended applicable to stratified lakes and reservoirs in temperate regions. However, the same study showed that the model is not applicable to reservoirs in which the area of cross section changes with depth. Studies by other workers (Ifeadi, December 5, 1973) using the model have found its correlation unsatisfactory.

Based on the basic relationship of Equation 2, other specific models were developed. One was on the effects of thermal discharges and the other was on the effects of interfacial mixing (Ifeadi, December 5, 1973).

Internal Radiation Absorption Models -

The internal radiation absorption models consider that solar radiation is absorbed both at the surface as well as at all depths within the water body to which the light penetrates. It has been observed that the neglect of internal heat absorptions (as in turbulent diffusion models) leads to artificially large values of eddy diffusivity (Dake and Harleman, April, 1969). Therefore, the exclusion of internal absorption makes the turbulent diffusion models of limited applicability. Several models will be discussed. They are very similar in their mathematical development, however they differ in their solution algorithms.

MIT Model. This model accounts for internal radiation absorption, boundary heat sources and sinks, and heat transport by advection, convection, and diffusion (Ryan and Harleman, April, 1971; Huber and Harleman, 1968; Huber, Harleman, and Ryan, April, 1972).

The output of the model is the prediction of the vertical temperature profile and the hydraulics of stratified flow.

Major geometrical simplifications and assumptions leading to the development of the model are (Ryan and Harleman, April, 1971):

1. Thermal gradients exist in the vertical direction only
2. Heat transport by turbulent mixing is accounted for only in the epilimnion region and only during times at which the temperature-induced density profile is unstable
3. Solar radiation is assumed to be transmitted in the vertical direction only

4. The sides and bottom of the reservoir are assumed to be insulated, the only heat crossing the boundaries (apart from the surface) is via inflow and outflow
5. The density (ρ), specific heat (c), and the coefficient of molecular diffusivity (α) are assumed constant in all heat budget and heat transport calculations
6. Solar radiation energy, transmitted by the water and intercepted by the reservoir sides, is assumed to be distributed uniformly over the cross section at the depth of interception.
7. Solar radiation is absorbed directly in the body of the fluid, as well as at the surface
8. Convection in the epilimnion is accounted for by allowing mixing to take place whenever the temperature gradient ($\partial T / \partial y$) is negative, *y is elevation, positive upwards)
9. Inflow enters the reservoir water column at the level at which its density matches that in the water column (NO outtrace mixing complication). Outflow is centered about the level of the outlet, i.e., linear temperature gradient in the vicinity of the outlet.
10. Gaussian inflow and outflow velocity profile is assumed
11. Outlet appears as a line sink, though in practice it is usually rectangular
12. Withdrawal may take place from several levels, single or concurrently
13. The vertical advective velocity is obtained by requiring that the continuity condition is satisfied at each level
14. The surface level is calculated as a function of the initial surface level and the cumulative inflow and outflow
15. Entrance mixing affects both the inflow and outflow velocity profiles and hence the vertical advection terms. Entrance mixing of 100 percent (or mixed inflow rate twice the stream inflow rate) is assumed.

Using the above assumptions and model characteristics, a basic heat transport equation is obtained from consideration of heat flow through a schematized control volume of the reservoir, thus (Ryan and Harleman, April, 1971):

$$\begin{aligned} \frac{\partial T(y)}{\partial t} = & \frac{\alpha}{A(y)} \frac{\partial}{\partial y} \left(A(y) \frac{\partial T(y)}{\partial y} \right) - \frac{1}{\rho c A(y)} \frac{\partial}{\partial y} \left(A(y) \phi(y) \right) \\ & - \frac{1}{A(y)} \frac{\partial}{\partial y} \left(V(y) A(y) T(y) \right) + \frac{1}{A(y)} \left(u_1(y) B(y) T_1 \right. \\ & \left. - u_o(y) B(y) T(y) \right) \end{aligned} \quad (3)$$

where

- $T(y)$ = temperature at elevation y
- $V(y)$ = vertical velocity at elevation y
- $u_1(y)$ = inflow velocity at elevation y
- $\phi(y)$ = radiation transmission at elevation (y)
- $u_o(y)$ = outflow velocity at elevation y
- T_1 = inflow temperature
- $A(y)$ = area at elevation (y)
- t = time
- α = molecular diffusivity
- y = elevation (positive upwards)

Equation 3 is solved numerically by explicit method with one initial condition,

$$T = T_o \text{ for all } y \text{ at } t = 0 \text{ (Beginning of spring),}$$

and two boundary conditions; namely, heat is conserved at the water surface and the reservoir bottom. Detail development and solution are given in Ryan and Harleman (1971).

The required input data are pertinent hydrological and meteorological parameters such as:

1. Solar radiation
2. Atmospheric radiation
3. Air temperatures
4. Relative humidities
5. Wind speeds
6. Streamflow rate
7. Streamflow temperature

Data from Fontana Reservoir were used to verify the mathematical model. The prediction was satisfactory. This model has wide applicability.

Water Resources Engineers Model -

This model also uses the internal radiation absorption approach. It is a general heat budget equation of the diagramaticized reservoir (Orlob and Selna, January, 1968).

The output of this model is the temperature distribution, and stratified flow patterns in the reservoir.

The general model is given as (Orlob and Selna, January, 1968):

$$a\theta_{,t} = a \left[\frac{hI}{c\rho} + (\phi_1\theta_1 - \phi_0\theta) \right] + \left[aA\theta_{,z} \right]_{,z} - \left[a\phi_v\theta \right]_{,z} \quad (4)$$

where:

$$\theta_{,t} = \frac{\partial\theta}{\partial t}$$

$$\left[aA\theta_{,z} \right]_{,z} = \frac{\partial}{\partial z} \left[aA \left(\frac{\partial\theta}{\partial z} \right) \right]$$

$$\left[a\phi_v\theta \right]_{,z} = \frac{\partial}{\partial z} \left[a\phi_v\theta \right]$$

- θ = water temperature
- θ_1 = temperature of inflowing water
- h^1 = heat flux per unit of water volume from external solar energy sources
- A = coefficient of effective diffusivity
- $\theta_z = \frac{\partial \theta}{\partial z}$
- C = heat capacity of coats
- ρ = density
- ϕ_v = advection velocity normal to the plan of a
- ϕ_o = flow withdrawn from the slice at an impoundment outlet
- ϕ_1 = flow advected to the slice in the horizontal plane

Major assumptions are:

- Vertical energy transfer down the water column
- Net shortwave energy distribution function beneath the water surface is a decaying exponential function
- The effective mixing processes which occur in the epilimnion are accounted for in the model by a variable effective diffusion coefficient
- Density profile is represented by a step function.

The primary input data are: Hydrologic, meteorologic, and climatic conditions of the reservoir. Specifically they include cloudiness, dry-bulk temperature, wet-bulk temperature, barometric pressure, and wind velocity. Researchers have verified this model and found it to have great merit (Bacca, et.al., August, 1973). The following virtues have been cited:

- Extensive field application (e.g., Hungry Horse Reservoir, Lake Roosevelt, Fontana Reservoir, etc.)
- Breadth of documentation (Water Resources Engineers, Inc., 1969^a; Water Resources Engineers, Inc., August, 1968; Water Resources Engineers, Inc., 1969^b)
- Efficiency of computation

- A quasi-two-dimensional description of the temperature patterns, and
- Finer longitudinal discretization of a reservoir.

The prime advantage of this model is that it can be used to obtain more detailed descriptions of temperature structures, flow patterns, and quality states.

Temperature Prediction Downstream

The temperature prediction in the deep reservoir differs from downstream and estuary prediction approaches. The major difference comes from the stratification of deep reservoirs. Downstream and estuary are continually mixed by the action of gravity flows, current, and wind agitation. To a lesser extent shallow reservoirs are mixed by wind agitation. Therefore they can be considered to be uniform in temperature with vertical temperature profile.

The major temperature related change in stream conditions occurring downstream from a reservoir is the replacement of a relatively homogeneous stream temperature condition with a condition of zones of markedly different temperatures. Immediately downstream of the reservoir outfall, water temperatures will be colder than natural stream conditions if the water is withdrawn from the lower layers of the reservoir. Farther downstream reduced flow will result in warmer stream temperatures through solar heating. Between these two zones of colder and warmer temperatures, a third zone will exist within which water temperature rises rapidly with distance. These temperature changes are important because of their impact on stream ecosystems and organisms. Marked temperature changes will cause alteration in the plant and animal species present in the stream, and in their rate of growth. Biological activity is highly temperature dependent and as a rough rule of thumb can be estimated as such activity would increase by the factor of 2 for each five degree Centigrade rise in stream temperature. Downstream temperature conditions will also influence chemical characteristics of the stream and chemical reaction rates. For example, the cooler water immediately below the outfall will possess higher levels of dissolved solids

in comparison to free flowing stream conditions. Since flow downstream from the reservoir will be reduced, at least during some portions of the year, downstream temperatures will be much more dependent than previously on the temperature conditions of new downstream inflows. Downstream tributaries with sewage or power plants, for example, may produce more significant temperature increases than previously. Conversely, any colder water tributaries from snow runoff will have a greater cooling effect than they would have had on the original freeflowing stream.

These potential downstream temperature effects are primarily dependent upon the source and rate of withdrawal from the reservoir and on the downstream tributary conditions. The potential for adverse impacts will be greatest when reservoir outflows are taken totally or primarily from the lower, cooler zone of the reservoir, and when irregular withdrawal rates result in periods of substantial reduced flow.

Temperature prediction in rivers and estuaries involves a complete heat balance of the body of water, which accounts for all heat initially present in the water and all heat that flows into and out of the water body during an interval of time.

The general time rate of temperature change is (Raphael, 1962):

$$\frac{dt_w}{dt} = \frac{Q_t A + m_i (t_i - t_w)}{m_w} \quad (5)$$

where

- t_w = river water temperature
- m_w = river water mass
- m_i = inflow mass of water
- t_i = inflow temperature of water
- Q_t = total net heat transfer/area
- A = area

The output of the model is the temperature profile. The primary input data are:

- Water body dimensions
- Flow and temperature characteristics
- Climatological and weather data.

The model is applicable in a uniform temperature region, and not applicable where a thermocline exists.

DISSOLVED OXYGEN AND BOD IMPACT AREA

Major Reservoir Influences on Dissolved Oxygen

The quantity of dissolved oxygen (DO) in the impoundment is a primary indicator of biological activity which in turn influences other chemical and biological activities of the water body such as biochemical oxygen demand (BOD), acidity, alkalinity, pH, etc. Aquatic life is oxygen dependent, as is the self-purification capacity of water released from an impoundment. Absence of dissolved oxygen may produce anaerobic conditions and resultant odors at the site. DO is known to vary over time and depth of the impoundment, thus the reduction of DO in the hypolimnion of thermally stratified impoundments following the onset of stratification during the summer season.

Three important types of dissolved oxygen impacts may be produced by reservoir construction. Thermal stratification discussed previously produces not only distinct temperature zones but also dissolved oxygen content zones. The colder bottom zone may display a distinct oxygen deficiency due to the lack of mixing and surface reaeration and due also to the increased dissolved oxygen uptake by chemicals released from the bottom sediments through the activities of anaerobic organisms. A second potentially major impact is that reaeration of the surface layer may be reduced and may become more dependent on climatic conditions, especially wind, rather than on flow rate. Since the surface waters are warmer their capacity to retain the dissolved oxygen will be reduced. The general effect of these impacts is that both the upper and lower zone may show lower levels of dissolved oxygen than were present in the free flowing stream.

These dissolved oxygen changes are of great significance because of the sensitivity of fish and other aquatic organisms to dissolved oxygen

levels. Reductions in dissolved oxygen may produce major changes in the species composition of the reservoir. These dissolved oxygen conditions may also produce a cycle of major stress periods occurring primarily in the late summer and fall when warm surface temperatures and algae die off may produce significant fish kills. Dissolved oxygen deficiencies in the bottom layer of the reservoir may also contribute significantly to the release of toxic chemicals trapped in bottom sediments since low DO levels will favor the activity of anaerobic organisms. Because dissolved oxygen levels are closely coupled with water temperature, the conditions under which the oxygen deficiencies may occur are similar to those under which marked temperature changes may take place. Oxygen deficiencies may occur in reservoirs deep enough to permit thermal stratification. Deficiencies may also result if there is little summer inflow and a long retention time. Conditions of high summer temperature and little wind mixing will also present prime circumstances for oxygen deficiencies. If the water flowing into the reservoir is either warm or high in salt concentrations the water's capacity to retain dissolved oxygen will also be reduced.

Potential sources of oxygen for the reservoir system include: (a) the inflow, (b) atmospheric reaeration, and (c) photosynthesis. The potential oxygen sinks are: (a) the outflow, (b) oxidation reactions, including biochemical oxidation of soluble or suspended organic materials (BOD), biochemical oxidations occurring at the mud/water interface, and occasionally chemical oxidation reactions when chemically reduced products of anaerobic decomposition are transported from a zone of oxygen deficiency to an aerobic area, and (c) respiration of animals and green plants in the absence of sunlight (Burdick and Parker, 1971).

The magnitudes and importance of the various sources and sinks vary quite widely in different water body systems and these factors may vary with time as well as location within the same water body. To a very large extent the variability of the factors involved in the oxygen balance of reservoirs is controlled by the temperature, the thermal density structure, and the hydraulic properties of the reservoir. For this reason, any comprehensive consideration of the reservoir oxygen balance must first consider the temperature distribution and its changes with depth and time as discussed above.

Since the primary sources of oxygen in a reservoir are usually more closely related to the reservoir surface zones (atmospheric reaeration, photosynthesis, and sometimes inflow), the development of thermal stratification (which changes the vertical mixing characteristics of the reservoir) reduces the rate at which oxygen is supplied to the deeper zones of the reservoir. This fact becomes even more significant when it is considered that a considerable fraction of the overall potential reservoir oxygen sinks frequently lie below the thermocline through which oxygen transport is inhibited.

Another important aspect of the reservoir thermal structure, in addition to the hydraulic implications, is the temperature itself. An example of such temperature effect is shown in Figure 3. Here impoundment effects and temperature with respect to deoxygenation rate, K_1 , and reaeration rate, K_2 , are depicted. It is observed that impoundment, K_1 , at a given temperature is unchanged, while the value of K_2 at any temperature is significantly reduced (Krenkel, Thackston, and Parker, February, 1969). In the hypolimnion, where the temperature remains somewhat low, the rate at which oxygen is extracted by biochemical oxidations, both within the water body itself and at the mud/water interface, is somewhat lower than it would be at higher temperatures. At the higher epilimnion temperatures, oxygen uptake proceeds at a more rapid rate, but, since oxygen is usually more readily available in this zone, its more rapid removal may be less critical. Another important aspect of temperature is its effect upon the solubility of oxygen. Oxygen is more soluble in water at lower temperatures, consequently a higher concentration of oxygen exists in the hypolimnion of an impoundment at the onset of stratification than if the temperature were higher. This fact, coupled with the reduced rate of hypolimnion BOD exertion noted before, may represent a slight positive effect upon the oxygen conditions of the hypolimnion. In the epilimnion, with the progression of warmer temperatures, the oxygen solubility is decreased while the rate of oxygen utilization is increased, which is a somewhat negative effect. An additional consequence of reduced oxygen solubility in the epilimnion is that a major portion of the oxygen produced by photosynthesis may be lost to the atmosphere, thereby reducing much of the potential benefit of photosynthesis. (As noted previously, the death of the photosynthetic organisms in the epilimnion and

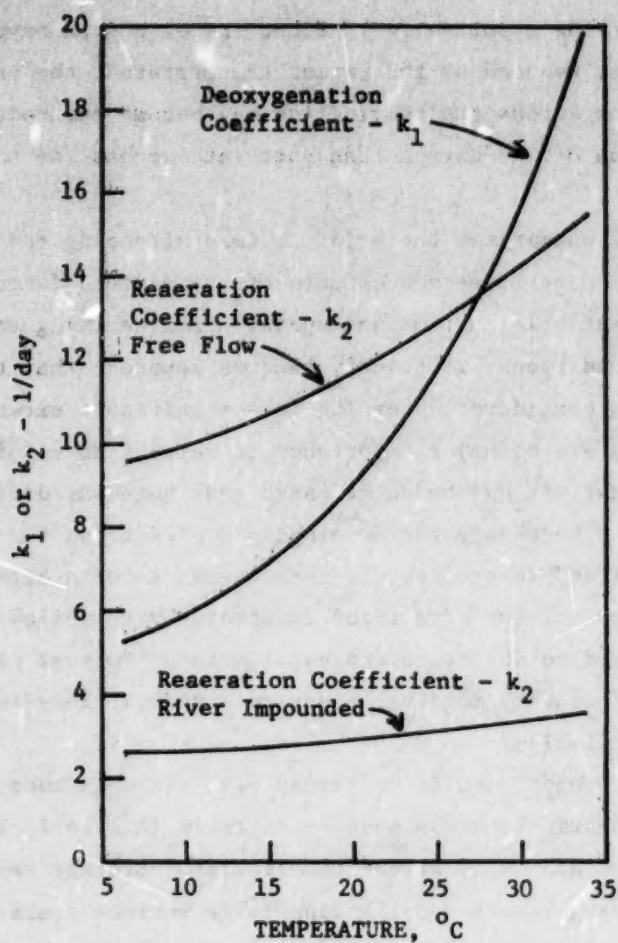
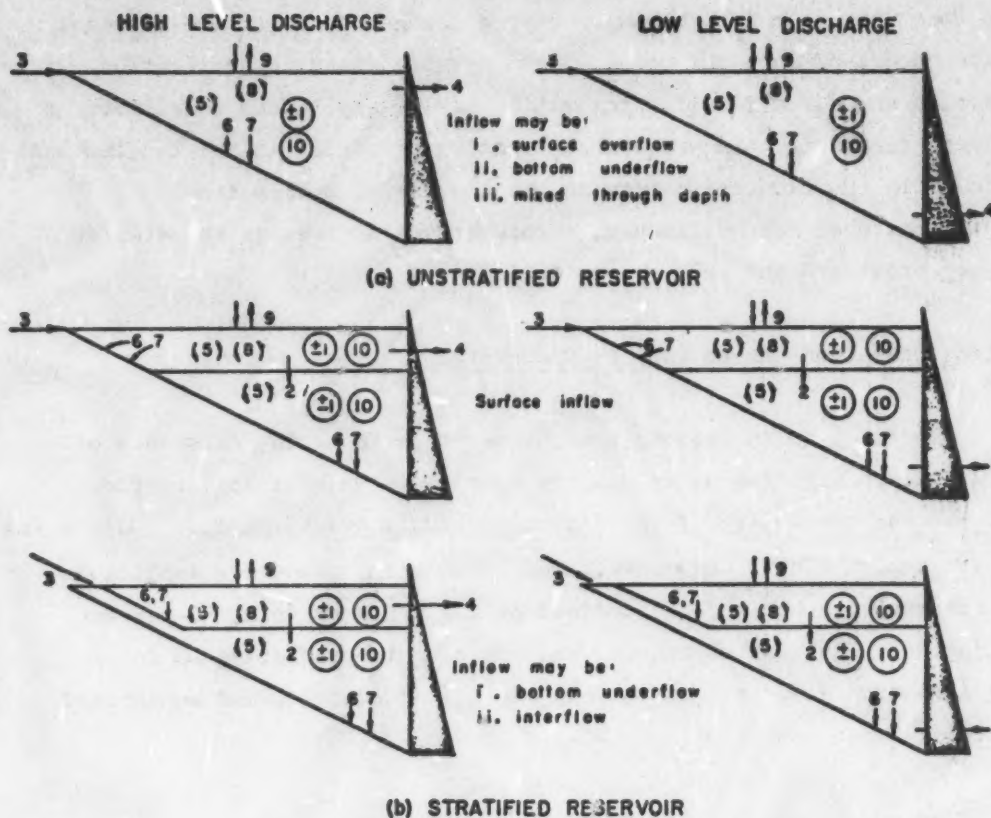


FIGURE 3. VARIATION OF k_1 AND k_2 WITH TEMPERATURE AND RIVER CONDITION (O'Connell and Thomas, 1965)

their subsequent sedimentation into hypolimnion can significantly affect the oxygen resources of the hypolimnion.) Since the dissolved oxygen concentration in the epilimnion is reduced by the warmer temperatures, the gradient of oxygen concentration across the thermocline may become reduced, leading to an additional reduction of the oxygen transport rate across the thermocline to the hypolimnion.

Figure 4 summarizes the major factors affecting the oxygen balance of reservoirs. The magnitudes and effects of the various factors are quite inter-related and variable in time and space. In attempting to describe reservoir oxygen conditions, it quickly becomes apparent that the constraints of the system being considered determine to a significant extent which sources and sinks of oxygen are of major importance in various zones of the reservoir. Recognizing this fact, it can be anticipated that somewhat different assumptions would be necessary for developing descriptions for stratified, as opposed to unstratified reservoirs, or for reservoirs with high level outlets or low level outlets, or for stratified reservoirs with inflow to the epilimnion as opposed to inflow to the hypolimnion. In some cases it might be desirable, for instance, to develop separate descriptions for the epilimnion and hypolimnion.

A further constraint is concerned with the magnitude of the inflow and outflow. The distinction was made by Kittrell (Kittrell, 1959) between "storage reservoirs" and "main stream reservoirs". Storage reservoirs were characterized as being rather deep, having large surface areas, having considerable fluctuations of surface elevation, having low flow velocities (long residence times) and usually developing persistent thermal stratification with hypolimnetic oxygen deficiencies during the summer months. Main stream reservoirs were viewed as being shallower, with much of the water being confined to the original river channel, having rather constant surface areas and water surface elevations, having high flow rates (short residence times), and developing less persistent thermal stratification and less severe hypolimnetic oxygen deficiencies (if any at all). Carried to the extreme, such a comparison would distinguish between a lake with essentially no outflow and an essentially unimpounded river. From the standpoint of mathematical description, a distinction between these contrasting cases would need to be made with respect to the dimension in which



MAJOR FACTORS AFFECTING OXYGEN BALANCE

- | | |
|---------------------------------|--|
| 1. CHANGE OF STORAGE | 6. BOTTOM AND VEGETATION DEMAND |
| 2. TRANSPORT ACROSS THERMOCLINE | 7. SEDIMENT DEMAND |
| 3. ADVECTION INFLOW | 8. NET PHOTOSYNTHESIS |
| 4. ADVECTION OUTFLOW | 9. SURFACE REAERATION |
| 5. INTERNAL OXYGEN CONSUMPTION | 10. TEMPERATURE INDUCED CHANGES (SOLUBILITY) |

FIGURE 4. IDEALIZED REPRESENTATION OF OXYGEN BALANCE CONSIDERATIONS FOR VARIOUS PHYSICAL CONSTRAINTS (From Burdick and Parker, 1971)

the primary changes of oxygen occur, since the application of three-dimensional models has not yet proven to be feasible. For the lake or storage reservoir in which the major oxygen changes occur in the vertical direction, a one-dimensional model may be a satisfactory approximation. Similarly, a one-dimensional approximation may be applicable to a river or main stream reservoir case where changes occur primarily in the longitudinal direction. In the transition between the two cases, mathematical description becomes more difficult, although combinations of the simpler models may provide a suitable approximation.

Predicting Dissolved Oxygen (DO) in Reservoirs

Modeling DO in impoundments is complicated by the existence of stratification, differing water quality conditions in a stratified flow medium, and the complexity of the entire reservoir hydrodynamics. Only a few models are applicable to deep stratified reservoirs. Many are applicable to the reservoir euphotic zone (defined as the depth by which 99 percent of the incident light is observed), and are used in predicting DO in flowing streams. Some of these models are discussed below and summarized in Table 3.

One-Dimensional Mathematical Model -

This is an oxygen balance model for an incremental volume of surface area A, and depth, dz. It involves formulating the rate change in total mass of DO within the horizontal slice and equating it to the sum of all DO import and removal rates, thus (Bella, October, 1970)

$$\frac{\partial(AC)}{\partial t} dz = F_i - F_o + S, \quad (6)$$

where

- C = the DO concentration within the slice
- t = time
- dz = incremental depth

TABLE 3. SELECTED DO MODELS FOR RESERVOIRS

Model	Assumptions/Conditions Applicable	Parameters Measured	Reservoir Modeled	Reference
1. One Dimensional Mathematical Model	Horizontal area constant with time Horizontal DO variations are negligible Applicable to stratified medium	Flux of DO at the surface Temperature profile Vertical dispersive coefficients Advective DO concentrations		Bella, 1970
2. Statistical Method	Useful in completely mixed (back water) reservoir Describes DO at sag point downstream from a waste input	Temperature Volume flow rate BOD		Krenkel, et.al., 1969
3. Multiple Regression Technique	Applicable in modeling BOD, COD, nutrients Useful in euphotic zones	Temperature profile Operational data for the reservoir	Satisfactorily used for Watanga, South Holston & and Norris reservoir	Churchill and Nicholas, 1967
4. Water Quality Model	Applicable to stratified flows Applicable to modeling DO, BOD, nutrients, algae population Vertical gradients in area and diffusion coefficients negligible	Reservoir dimension Flow characteristic	Model has not been verified	Bacca, et.al., 1973

- P_i = the DO flux into the slice
 P_o = the DO flux out of the slice, and
 S = the sum of all DO sources and sinks acting on the slice.

Based on the above oxygen balance, the general vertical one-dimensional DO equation for lakes was developed: (Bella, October 1970)

$$\frac{\partial C}{\partial t} = \frac{1}{A} \left[\frac{\partial \left(D_v A \frac{\partial C}{\partial z} \right)}{\partial z} - \frac{\partial (UAC)}{\partial z} - q_e C + q_i C_i + (P - R) \right] \quad (7)$$

where

- C = the DO concentration
 A = horizontal area, constant with time
 D_v = the vertical dispersion coefficient
 U = the average water velocity across the horizontal area
 q_e = rate of water exported per unit of depth
 q_i = the rate of water imported per unit of depth
 C_i = the DO concentration in the imported water
 R = the rate of DO change per unit volume due to total community respiration, such as algae respiration, BOD removal, and shore-bottom demand
 P = rate of oxygen production by algae

The output of the model is the prediction of DO distribution with depth and time in stratified lakes or reservoirs. The model can be used to determine hypolimnetic oxygen demand rates by way of explicit finite-difference approximation.

Primary assumptions are that:

- Horizontal areas are constant with time and
- Horizontal DO variations are small compared with vertical variations.

The one-dimensional continuity equation for a constant area is:

$$\frac{d(UA)}{dz} = q_i - q_e . \quad (8)$$

Input data to the model are:

- The flux of DO at the water surface, F_H which is given as:

$$F_H = A_H K_L (C_S - C_H) , \quad (9)$$

where

- K_L = the surface DO transfer coefficient
- C_S = DO concentration at the surface
- C_H = DO concentration below the surface.

- Temperature profile
- Vertical dispersive coefficients
- DO sources and sinks acting on the water body.

Equation (7) may be further simplified to take care of special situations (Bella, October, 1970). The model has been verified in stratified flows, and correlation was found satisfactory.

Statistical Method -

This method was used to estimate the DO of a completely mixed reservoir. The data obtained were statistically analyzed and the regression equation, which described conditions at the sag point downstream from a waste input was (Krenkel, Cawley, and Minch, September, 1965):

$$DO = 57.8 \frac{Q^{0.001}}{BOD^{0.1} T^{0.51}} , \quad (10)$$

where

Q = capacity

T = temperature.

Multiple Regression Technique (Principal Component Analysis) -

Principal component analysis is said to minimize the effects of intercorrelations among the "independent" variables and yields a prediction equation in which the coefficient of an "independent" variable, X, more nearly represents the change in Y per unit change in the corresponding X. Three dependent variables, retention time, temperature of the outflow, and distance are combined in a regression equation, thus

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1^2 + b_5X_2^2 + b_6X_3^2, \quad (11)$$

where

Y = decrease in DO concentrations (mg/liter) between 1 and the date for which a DO prediction is desired

a = constant determined from the solution of the equation

X_1 = T/10 where T = time (days) from April 1 to the date for which a DO prediction is desired.

$$X_2 = \sum_{i=1}^n \left(\frac{T}{10} \right)_i \Delta T_{e_i}, \quad (12)$$

where

n = the number of 10-day time increments after April 1

ΔT_e = increase in temperature, ($^{\circ}\text{C}$) between April 1 and the date for which a DO prediction is desired, and

$$x_3 = \sum_{i=1}^n \frac{T}{10H_i} \quad (13)$$

where

H = the distance (feet) above the centerline of the power intake at which the April 1 inflow exists on the date of interest, assuming no mixing in the pool and that water is drawn from the pool at the elevation of the intake only.

Primary input data are the operational data for the reservoir, and the predicted values of the temperature of the outflow.

This model showed satisfactory prediction of DO values for Watanga, South Holston, and Norris reservoirs. However, their stratification conditions were not stated.

This technique has the advantage of being expanded to take several pertinent water quality factors (such as BOD, COD, nutrients, etc.) in the inflow into account and thus allowing more accurate predictions to be made for reservoirs covering a wide range of project design, operation, and water quality conditions (Churchill and Nicholas, December, 1967).

Water Quality Model -

This model approximates the formulation of the overall quality problem in the reservoir by partitioning the mechanisms of change of some water quality parameters into mass transport and chemical reactions. Utilizing the segment-element discretization, the mass transport equations are derived for the finite layer (element) of solute transport as (Bacca, et.al., August, 1973):

$$\frac{\partial C^{(k)}}{\partial t} = D_z \frac{\partial^2 C^{(k)}}{\partial z^2} - \frac{Q^v}{A} \frac{\partial C^{(k)}}{\partial z} + \frac{1}{A\Delta z} (Q_1^h C_1^{(k)} - Q_0^h C^{(k)}) + S^{(k)} \quad (14)$$

where

- $C^{(k)}$ = concentration of k^{th} constituent, $k = 1, 2, \dots, n$
- $C_1^{(k)}$ = concentration of upstream flow
- D_z = effective diffusion coefficient
- A = horizontal surface area of water plane for element
- Q^v = vertical flow through element (layer)
- Q_1^h, Q_o^h = horizontal inflow (i) and outflow (o) to element
- Δz = element thickness

This model may be used to describe the spatial and temporal variations of several reservoir water quality parameters, such as dissolved oxygen, BOD, algae populations, and nutrient materials.

Main assumptions are:

- Vertical gradients in area and diffusion coefficients are neglected
- Boundary conditions for the transport equations as $\partial C^{(K)} / \partial n = 0$ at the bottom and air-water interface.

This model has not been verified and thus its correlation with natural systems is not yet known.

DO and BOD Prediction in Streams and Estuaries

Downstream dissolved oxygen impacts parallel temperature impacts. That is, a stable and homogeneous stream environment is replaced by an unstable environment varying markedly over time and distance. Extreme dissolved oxygen deficiencies may occur immediately downstream from the reservoir, especially if the outflow water is withdrawn from the reservoir's bottom layers. Periods of reduced flow will result in a lowering of the reaeration rate downstream from the reservoir. The downstream reach previously homogeneous in regard to dissolved oxygen may show a steep gradient with DO levels increasing with distance from the reservoir. Because of reduced flows downstream, tributaries to the main stream will become more important determinants of dissolved oxygen levels. If waters are drawn from

the lower portions of the reservoir they will be high in reduced chemicals increasing the physical/chemical oxygen demand in the downstream reach. The net effect of these impacts on downstream waters is that the capacity of the stream to retain dissolved oxygen may be reduced at the same time that the demand for oxygen for physical/chemical and biological processes may be increased. Significant downstream oxygen deficiencies may thus be produced, resulting in major changes in plant and animal populations of the stream.

Oxygen deficiency problems, like temperature problems, will be greatest in a downstream area where water from the reservoir is withdrawn only from the bottom layers and/or when wide variations in the rate of withdrawal occur seasonally, producing periods of extreme low flow.

The general equation describing dissolved oxygen in streams, estuaries and the euphotic zone of reservoirs may be represented as (Bacca, et.al., August, 1973):

$$\begin{aligned} \frac{dDO}{dt} = & -k_1^c L_c - K_1^n L_n - \frac{k_4 L_d}{H} + k_2 (DO_s - DO) \\ & + (P-R)_s + (P-R)_a \end{aligned} \quad (15)$$

where

- DO = dissolved oxygen, mg/l
- k_1^c, k_1^n, k_4 = deoxygenation rates for carbonaceous, nitrogenous, and benthic BOD, / day
- k_2 = reaeration coefficient, /day
- $(DO_s - DO)$ = dissolved oxygen deficit
- $(P-R)_s, (P-R)_a$ = photosynthesis and respiration rate for suspended and attached algae, respectively
- T = temperature
- L_c = carbonaceous BOD, in mg/l
- L_n = nitrogenous BOD, in mg/l
- L_d = oval benthic BOD, in mg/m^2
- H = average river depth, in meters

Two simpler forms of Equation 15 describing the concentration of DO in streams are those described by O'Connell, et.al. (1965), and Symnon, et.al. (1969), and that of a pure mixed water. Stream DO prediction models are summarized in Table 4.

$$\frac{dD}{dt} = K_1(La - y) - K_2D + (R - P) \quad (16)$$

where

- D = oxygen deficit
- t = time
- K_1 = deoxygenation rate constant
- La = total organic BOD
- y = $La[1 - \exp(-K_1 t)]$ BOD satisfied at any time
- K_2 = reoxygenation rate constant (atmospheric)
- R = rate of oxygen demand by algae, and
- P = rate of oxygen production by algae.

An important assumption of this model is that sedimentation does not occur. Also the model has a shortcoming in not predicting the DO conditions of the hypolimnion where DO deficiencies appear. It is also unable to account for the diffusive DO transport from the euphotic zone to greater depths.

The model has been evaluated by the DO Probe Method (Langbien and Durum, 1967) and its correlation found satisfactory. Therefore the model is a useful method for studying the DO budget in streams, and euphotic impoundments. It will also permit comparison of the DO budget from one impoundment to another.

DO of Mixed Pure Water (Bacca, et.al., August, 1973) -

The rate of reaeration of well-mixed pure water is proportional to the oxygen saturation deficiency, thus:

$$\frac{dDO}{dt} = k_2 (DO_s - DO) \quad (17)$$

TABLE 4. DO PREDICTIONS IN STREAMS AND EUPHOTIC ZONE OF RESERVOIRS

Model/Authors	Primary Assumptions/ Conditions Applicable	Primary Input Parameters
Bacca, et.al., 1973	• Wind effect is insignificant • Vertical dispersive effects insignificant • Applicable to streams and completely mixed euphotic zone of reservoir • Not applicable to stratified zones of lakes and reservoirs	• Deoxygenation coefficient(s) • Reaeration coefficient(s) for carbonaceous, nitrogenous, and benthic substances • Dissolved oxygen deficits • Photosynthesis and respiration rate for suspended and attached algae
O'Connell, et.al., 1969	• Sedimentation does not exist • Wind effect is insignificant	• Deoxygenation coefficient • Reaeration coefficient for carbonaceous substances
Symon, et.al., 1968	• Vertical dispersive effects insignificant • Applicable to streams and completely mixed euphotic zone of reservoir • Not applicable to stratified zones of lakes and reservoirs	• Dissolved oxygen deficit • Photosynthesis and respiration rate for attached algae
Mixed Pure Water Model/Bacca, et.al., 1973	• Carbonaceous, nitrogenous, and benthic deoxygenation effects negligible • Photosynthesis and respiration of suspended and attached algae negligible • Not applicable to stratified zones of lakes and reservoirs • Applicable to only pure mixed streams	• Dissolved oxygen deficit • Reaeration coefficient

where

- DO = dissolved oxygen concentration, mg/l
- DO_s = saturated dissolved oxygen concentration, mg/l
- k₂ = reaeration coefficient: 0.05-16.0/day

The value of DO_s for natural, unpolluted streams can be calculated from the following equation:

$$DO_s = 14.652 - 0.41022T + 0.0079910T^2 - 0.000077774T^3$$

The model is not applicable in polluted streams.

Reaeration Coefficients -

The reaeration process is significantly influenced by temperature, stream geometry, and stream hydraulics.

The reaeration coefficient has been found to vary with temperature as:

$$K_2 = K_2(20) \theta^{(T-20)} \quad (18)$$

where

$$1.015 \leq \theta \leq 1.047 \text{ (Bacca, et.al., August, 1973)}$$

K₂ = coefficient at temperature T

K₂(20) = coefficient at 20°C.

Numerous equations have been developed to compute reaeration coefficients based on stream geometry and stream characteristics (Texas Water Development Board, May, 1971). However, most are extensions of a basic equation given by Streeter and Phelps (Streeter and Phelps, 1958 [reprinted]):

$$K_2 = \frac{c\bar{u}^n}{D^2} \quad (19)$$

where

$\bar{u}$ = mean stream velocity, ft/sec
 D = mean stream depth, ft, and
 c, n = constants for a particular stream in question.

Several reaeration coefficient models follow:

- General velocity-depth model (Bacca, et.al., August, 1973):

$$K_2 = r_1 \frac{v^{r_2}}{h^{r_3}} \quad (20)$$

where

K_2 = reaeration coefficient, /day
 v = velocity, ft/sec
 h = depth, ft
 r_1, r_2, r_3 = constants: 2.0-12.0, 0.6-1.0, 0.85-1.85

- Churchill, Elmore, and Buckingham (Churchill, Elmore, and Buckingham, 1962):

$$K_2^{20} = 5.026 \bar{u}^{0.969} D^{-1.673} \times 2.31 \quad (21)$$

where

$\bar{u}$ = average velocity in the stream, ft/sec
 D = average depth of the stream, ft, and
 K_2 = reaeration coefficient, (days)⁻¹

- Langbien and Durum (Langbien and Durum, 1967):

$$K_2^{20} = 3.3 \bar{u}/D^{1.33} \quad (22)$$

where

$\bar{u}$ = mean velocity, ft/sec

D = mean depth, ft, and

K_2 = reaeration coefficient, (days)⁻¹

- O'Conner and Dobbins (O'Conner and Dobbins, 1958). These investigators proposed equations based on the turbulent characteristics of a stream as follows:

For streams displaying low velocities and isotropic conditions:

$$K_2^{20} = \frac{(D \bar{u})^{0.5}}{D^{1.5}} \quad (23)$$

For streams displaying high velocities and nonisotropic conditions:

$$K_2^{20} = \frac{480 D_m^{0.5} S_o^{0.25}}{D^{1.25}} \times 2.31 \quad (24)$$

where

S_o = slope of the streambed

D = mean stream depth, ft

$\bar{u}$ = mean velocity, ft/day

K_2 = reaeration coefficient, (days)⁻¹

and where D_m is the molecular diffusion coefficient (ft^2/day) which can be computed by

$$D_m = 1.91 \times 10^{-3} (1.037)^{T-20} \quad (25)$$

Isotropic conditions are satisfied when Chezy's coefficient is greater than 17, and non-isotropic for values less than 17. O'Conner and Dobbins (1958) have shown that Equation 16 is generally applicable for most cases.

- Owens, Edwards, and Gibbs (Owens, Edwards, and Gibbs, 1964):

For streams with a velocity variation range from 0.1 to 5.0 ft/sec and depths from 0.4 to 11.0 ft:

$$K_2^{20} = 9.4 \bar{u}^{0.67} / D^{1.85} \times 2.31 \quad (26)$$

where

$\bar{u}$ = mean velocity, ft/sec

D = mean depth, ft, and

K_2 = reaeration coefficient, $(\text{days})^{-1}$

For streams with a velocity variation range from 0.1 to 1.8 ft/sec and depths from 0.4 to 11.0 ft:

$$K_2^{20} = 10.1 \bar{u}^{0.73} / D^{1.75} \times 2.31 \quad (27)$$

- Thackston and Krenkel (Thackston and Krenkel, February, 1969). This investigation included several rivers in the Tennessee Valley Authority system and resulted in the following equation for K_2 at 20°C :

$$K_2^{20} = 10.8 (1 + F^{0.5}) \frac{u^*}{D} \times 2.31 \quad (28)$$

where F is the Froude number which can be computed by

$$F = \frac{u^*}{\sqrt{gD}} \quad (29)$$

and u^* is the shear velocity, ft/sec, which can be computed by

$$u^* = \sqrt{DS_e g} \quad (30)$$

where

- D = mean depth, ft
- g = acceleration of gravity, ft/sec², and
- S_e = slope of the energy gradient.

• Dobbins (Dobbins, June, 1964):

$$K_2 = \frac{.2772 C_A E^{3/8} \coth \frac{BE^{1/8}}{C_4^{1/2}}}{C_4^{3/2} h} \quad (31)$$

where

$$C_4 = 0.9 + \frac{v}{\sqrt{gh}}$$

$$C_A = 1.0 + \left(\frac{v}{\sqrt{gh}} \right)^2$$

$$E = 30 v S$$

V = velocity in ft/sec.

S = river channel slope

$$\begin{aligned}
 A &= 9.68 + 0.054 (T-20) \\
 B &= 0.976 + 0.0137 (30-T)^{3/2} \\
 g &= \text{gravitational constant, ft/sec}^2 \\
 T &= \text{temperature, } ^\circ\text{C}
 \end{aligned}$$

Photosynthesis and Respiration of Attached Algae and Benthic Plants -

The net rate of photosynthesis and respiration of attached algae and benthic plants is given as (Bacca, et.al., August, 1973):

$$(P-R)_a = A_1^a \cos(\omega_a t + \phi_a) + A_2^a \cos(2\omega_a t + \alpha_a) \quad (32)$$

where

$$\begin{aligned}
 (P-R)_a &= \text{net rate of photosynthesis and respiration,} \\
 &\quad \pm (0.01-2.00), \text{ mg/l per day} \\
 \omega_a &= \text{period, days} \\
 A_1^a, A_2^a, \phi_a, \alpha_a &= \text{constants}
 \end{aligned}$$

Photosynthesis and Respiration of Suspended Algae -

The rate of photosynthesis and respiration of suspended algae is given as a two-term harmonic function of the form (Bacca, et.al., August, 1973):

$$(P-R)_s = A_1 \cos(\omega t + \phi) + A_2 \cos(2\omega t + \alpha) \quad (33)$$

where

$$\begin{aligned}
 (P-R)_s &= \text{net rate of photosynthesis and respiration,} \\
 &\quad \pm (0.1-2.0), \text{ mg/l per day} \\
 \omega &= \text{period, days} \\
 A_1, A_2, \phi, \alpha &= \text{constants}
 \end{aligned}$$

Biochemical Oxygen Demand -

A model using first order BOD reactions can be used to describe the carbonaceous and nitrogenous components of BOD, thus (Bacca, et.al., August, 1973):

$$\frac{dL_c}{dt} = - (k_1^c + k_3^c) L_c + P_c$$
$$k_1^c = k_1^c(20) \theta_c^{(T-20)} \quad (34)$$

$$\frac{dL_n}{dt} = - k_1^n L_n$$
$$k_1^n = k_1^n(20) \theta_n^{(T-20)} \quad (35)$$

where

- L_c = carbonaceous BOD, mg/l
- k_1^c = deoxygenation coefficient
- k_3^c = sedimentation coefficient: 0.0-3.5/day
- P_c = scour coefficient: 0.0-0.8 mg/l per day
- $k_1^c(20)$ = deoxygenation coefficient at 20°C: 0.0-0.8/day
- θ_c = temperature coefficient: 1.02-1.06
- T = temperature, °C
- L_n = nitrogenous BOD, mg/l
- k_1^n = deoxygenation coefficient: 0.1-0.8/day
- $k_1^n(20)$ = deoxygenation coefficient at 20°C
- θ_n = temperature coefficient: 1.05

c = denotes carbonaceous

n = denotes nitrogenous

Second-order equations are also in the literature but they have been observed not to predict BOD concentrations with any more accuracy than the first order equations which require less data (Bacca, et.al., August, 1973).

Benthic Oxygen Demand -

The benthic oxygen demand is a steady state or first-order reaction. This is given as (Bacca, et.al., August, 1973):

$$\frac{1}{H} \frac{dL_d}{dt} = -k_4 \frac{L_d}{H} - P_c + k_3^c L_c \quad (36)$$

$$k_4 = k_4(20) \theta_d^{(T-20)} \quad (37)$$

where

- L_d = areal benthic BOD, mg/m^2
- k_4 = deoxygenation coefficient for benthic BOD
- $k_4(20)$ = deoxygenation coefficient at 20°C : 0.0-0.8/day
- θ_d = temperature coefficient: 1.05
- H = average river depth in meters
- P_c, k_3^c, L_c are defined above

This equation is coupled to the carbonaceous BOD equation through the constants P_c, k_3^c , and L_c .

CHEMICAL IMPACT AREA

Major Reservoir Influences on Chemical Constituents and Chemical Activity

The inflow water quality, the character of the reservoir soils, and biological activity control the chemicals, trace elements, and chemical reactions in reservoirs. Parameters like carbon dioxide, pH, alkalinity, and hardness control the chemical activity and are interrelated through the carbonate equilibrium relationships. They exert influences upon changes of other water quality parameters too, as well as upon each other. Another factor is the increased detention time of water in the reservoir which provides a potential opportunity for slow reactions to come closer to completion. Thermal stratification and its aligned effect on oxygen conditions also influence the distribution of these parameters in reservoirs with depth and time. For example, the hypolimnion of a stratified reservoir tends to develop higher concentrations of free carbon dioxide, lower pH, higher total alkalinity, higher hardness, and higher values of specific conductance than the epilimnion (Burdick and Parker, 1971).

Several important changes in the chemical characteristics of a stream may occur following impoundment. Longer retention time and increased surface area, may increase evaporation and thus increase salt concentrations. Reduced flow rates and incomplete mixing will result in increased sedimentation and the trapping of nutrients in bottom sediments. The action of anaerobic organisms may result in the release of chemicals or toxic materials from bottom sediments. Finally, periodic surges of concentrations of salts, nutrients, and toxic materials may occur at periods of spring and fall turnover.

These changes are important for a number of reasons. They may result directly in changes in the plant and animal population of the water body. They will decrease the oxygen holding capacity of the water. Trapping of nutrients may increase the biological activity in the reservoir and thus produce algal blooms. Surges occurring during turnover periods may result in the concentration of some materials not generally harmful reaching toxic levels, for example iron or manganese. Generally toxic materials otherwise trapped in bottom sediments such as mercury and copper may also

be released. Such undesirable alterations in the chemical constituents of a water body will be most likely to occur when the reservoir inflow is high in nutrients or toxic materials such as pesticides, when the natural inflow--particularly during summer--is greatly reduced but the inflow from industrial or sewage plants is constant, and when these conditions are coupled with temperature or dissolved oxygen conditions promoting a marked stratification and turnover cycle.

The primary alterations and chemical characteristics downstream produced by reservoir construction are: a reduction in nutrients and suspended solid levels, an increase in dissolved solids level, and the creation of a system more sensitive to new inputs from downstream tributaries.

These changes may be of particular importance because of their direct influence on plant and animal composition of the stream or on the level of biological activity. They may also be important to the extent they decrease the waste assimilative capacity of the stream. Perhaps more fundamentally, they result in the creation of a fragile system highly susceptible to outside stresses. Deleterious changes in stream chemistry are most likely to be produced by the same conditions creating water temperature and dissolved oxygen problems, that is, withdrawals from the bottom layer of the reservoir and significant variation in the rate of flow resulting in major periods of low flow. Chemical prediction models are summarized in Table 5.

Effects on Nutrients

There is increased nutrient build up of fertility in reservoirs, creating the same eutrophication problems that exist in many natural lakes. Important factors are increased nitrogen and phosphorus retention and loss of dissolved oxygen resources in the deep water hypolimnion, which may lead to algal blooms and other aquatic plant problems. Other conditions at the impoundment, such as light, suitable temperature, and quiescent water also contribute to algal growth.

The sources of nutrients are varied. It has been reported that a major source of nitrogen and phosphorus is the treated and untreated sewage from cities. For example, it has been estimated that approximately 0.27 mg/l

TABLE 5. CHEMICAL PREDICTION MODELS

Model/Authors	Primary Assumptions/ Conditions Applicable	Primary Inputs and Parameter Measured
Nitrogen Model/ Bacca, et.al., 1973	- Assumed that stratification does not exist - Applicable to conditions where algae effects are both significant and insignificant	- Concentrations of ammonia, nitrite, nitrate, and organic nitrogen - Concentrations of phytoplankton and zooplankton - Growth and death rates of the algae - Rate constants for ammonia, nitrite, nitrate, and organic nitrogen - Measures a particular nitrogen concentration per unit volume
Phosphorus Model/ Bacca, et.al., 1973	- Assumed that stratification does not exist - Applicable to reactions between soluble and sedimentary phosphorus and algae	- Concentrations of soluble and sedimentary phosphorus, and their rate constants - Concentrations of phytoplankton and zooplankton and their growth and death rates - Measures phosphorus concentration per unit volume
Toxic Compounds Model/Bacca, et.al., 1973	- Assumed that stratification does not exist - Model accounts for any order of decay for any toxic compound - Can be used to represent sorption, chemical transformation, sedimentation, biological uptake	- Concentration of the toxic compound - Rate constant - Order of the decay - Measures the concentration of the toxic substance per unit time
Chemical Reaction Model	- Assumed that stratification does not exist, and that the solution is completely mixed - Applicable to predicting general equilibrium rate constants	- Temperature of the medium - Activation energy - Measures the equilibrium constant

phosphorus and 1.35 mg/l nitrogen are discharged from sewage (Churchill, Elmore, and Buckingham, 1962). These values are higher than the minimum values that could support objectionable population density of algae which approximately 0.015 mg/l for phosphorus, and 0.3 mg/l for inorganic nitrogen. Significant quantities of nutrients may find their way into reservoir also from agricultural lands. The quantities leaving agricultural land are variable depending upon land use, slope, and soil characteristics. Typical contributions of about 2 pounds of phosphorus per acre per year, and between 0.06 to 3 pounds of nitrogen per acre by year have been noted (Love and Slack, 1963). Fertilizer application, feedlots and animal factories contribute their share to water bodies, especially when they are situated adjacent to water courses.

The nutrients that enter a given reservoir also recycle via the biological system. The nutrient substance of a given species is released upon death and decay and is made available for uptake by other organisms. Both the nitrogen and phosphorus cycles are rather complex. They exist in different forms and the recycle circle may be short to long. Another complication is the occurrence of stratification. Ammonia tends to build up in the hypolimnion of a stratified impoundment under reduced oxygen concentrations due to ammonification of organic nitrogen, reduction of nitrite and nitrate, and desorption of ammonium ions from the sediments. Phosphorus apparently accumulates in the hypolimnion of a stratified impoundment by sedimentation of organisms containing phosphorus from the surface and by diffusion from chemically reduced bottom muds.

In the epilimnion, due to aerobic conditions, nitrate is the form normally present unless it is extracted by the phytoplankton to form new cell material.

At present, there are no available models for reservoirs to predict, during the planning stages, what the absolute levels of nutrient production are likely to be though approximations may be developed based upon incoming stream loadings. The following two models deal instead with the cycling of nitrogen and phosphorus.

Nitrogen Model -

This nitrogen model consists of two parts: one considers the effects of algae while the other includes ammonia-nitrate dynamics. The concentrations of the various nitrogen forms are given by C_i and the rates of reaction are given by J_i . The various nitrogen components are formulated as a first-order model. The model is described by the equations (Bacca, et.al., August, 1973):

$$\frac{dC_1}{dt} = -J_1C_1 + J_3C_4 - G_P P A_{NP} \left[\frac{C_1}{C_1 + C_3} \right] \quad (38)$$

$$\frac{dC_2}{dt} = -J_2C_2 + J_1C_1 \quad (39)$$

$$\frac{dC_3}{dt} = J_2C_2 - G_P P A_{NP} \left[\frac{C_3}{C_1 + C_3} \right] \quad (40)$$

$$\frac{dC_4}{dt} = -J_3C_4 + D_P P A_{NP} + (D_Z - G_Z) A_{NZ} Z \quad (41)$$

where

- C_1 = ammonia concentration, mg/l
 - C_2 = nitrite concentration, mg/l
 - C_3 = nitrate concentration, mg/l
 - C_4 = organic nitrogen concentration, mg/l
 - J_1, J_2, J_3 = rate constants: 0.1-0.5, 5.0-10.0, 0.1-0.4/day
 - P, Z = phytoplankton and zooplankton concentrations, mg-C/l
 - A_{NP}, A_{NZ} = ratio of nitrogen to carbon in phytoplankton and in zooplankton: 0.17, 0.15 mg-N/mg-C
 - G_P, G_Z = growth rates of phytoplankton and zooplankton, /day
 - D_P, D_Z = death rates of phytoplankton and zooplankton, /day
- P, Z, G_P, G_Z, D_P , and D_Z are formulated in the algae model.

For conditions where algae effects are not significant, simple first-order ammonia-nitrate models are applicable:

$$\frac{dC_1}{dt} = -J_2 C_1 \quad (42)$$

$$\frac{dC_3}{dt} = +J_2 C_1 \quad (43)$$

Phosphorus Model

The phosphorus model developed by the same group of researchers consists of three parts (Bacca, et.al., August, 1973):

- The first-order reactions of soluble phosphorus with algae and with the sediments
- The first reaction model between soluble and sediment phosphorus
- The second-order decay model for soluble phosphorus.

The concentrations of the phosphorus forms are given by D_i , and the rate constants for the reactions are given by I_i .

The equations for this model are (Bacc, et.al., August, 1973):

$$\frac{dD_1}{dt} = -I_1 D_1 + I_2 D_2 + I_3 D_3 - G_P P A_{DP} \quad (44)$$

$$\frac{dD_2}{dt} = -I_2 D_2 + I_1 D_1 \quad (45)$$

$$\frac{dD_3}{dt} = -I_3 D_3 + D_P P A_{DP} + (D_Z - G_Z) A_{DZ} Z \quad (46)$$

where

- D_1 = soluble phosphorus concentration, mg/l
 D_2 = sedimentary phosphorus concentration, mg/l
 I_1, I_2, I_3 = rate constants: 0.1-0.7/day
 P = phytoplankton concentration, mg-C/l
 Z = zooplankton concentration, mg-C/l
 A_{DP}, A_{DZ} = ratio of nitrogen to carbon in phytoplankton and zooplankton: 0.17, 0.15 mg-N/mg-C
 G_P, G_Z = growth rates of phytoplankton and zooplankton, /day
 D_P, D_Z = death rates of phytoplankton and zooplankton, /day
 P, Z, G_P, G_Z, D_P , and D_Z are formulated in the algae model.

The first-order model assuming that only reactions between soluble and sedimentary phosphorus occur is given by:

$$\frac{dD_1}{dt} = -I_1 D_1 + I_2 D_2 \quad (47)$$

$$\frac{dD_2}{dt} = -I_2 D_2 + I_1 D_1 \quad (48)$$

while the second order is:

$$\frac{dD_1}{dt} = -I_1 D_1^2 \quad (49)$$

Effect of Toxic Compounds

The behavior of toxic compounds in an aquatic environment is variable and dependent upon the compound being modeled. Reservoirs do contain iron, manganese and other compounds which can be toxic at higher concentrations under certain environmental conditions.

Iron and manganese have been observed to cause color and turbidity resulting in potentially increased costs and staining upon water use, and incrustation of material that it contacts when reactions are conductive and

are present in sufficient concentrations. The sources of these two metals seem to be the rocks, soil, vegetation of the watershed, and sewage from which the metals are transported to the reservoir in solution and suspension. They are affected by oxidation and precipitation which may transfer them downward in the reservoir. The increase and decrease in concentration of the two metals roughly parallel the decrease and increase of dissolved oxygen. Hence these metals are more abundant at the hypolimnion where dissolved oxygen is depleted than at the epilimnion. Both the chemical and the physical properties are important. Iron and manganese are both insoluble in their oxidized forms, but are readily soluble in their reduced forms. When the oxidation-reduction potential of the hypolimnion becomes sufficiently reduced (usually due to severe oxygen deficiency) these ions become soluble and diffuse from the bottom muds into the overlying water. As the mud surface becomes reduced, phosphate and other ions are simultaneously mobilized. Iron may precipitate as insoluble ferrous sulfide under extremely reducing conditions. Under oxidizing conditions iron is precipitated as ferric hydroxide, and manganese as manganic oxide or as the manganous ion adsorbed on ferric or manganic oxide particles. The kinetics of the oxidation may not be very rapid, so that these ions may persist for some time in an oxidizing environment to produce the objectionable characteristic taste and color (Burdick and Parker, 1971).

A simple decay model has been proposed to describe toxic compounds (Bacca, et.al., August, 1973). This model accounts for any order of decay desired, including zero order, and nonlinear behavior. The model is given as (Bacca, et.al., August, 1973):

$$\frac{dT_c}{dt} = - aT_c^n \quad (50)$$

where

- T_c = concentration of toxic compound
- a = rate constant (a function of toxic compound and media characteristics, experimentally determined.)
- n = order of decay.

This decay model can be used to represent any of the mechanisms of exchange such as chemical transformations, sedimentation, biological uptake, and sorption.

Effect of Chemical Reactions

Impoundment can lead to significant shifts in the chemical reaction in the impounded water. Due to stratification and increased detention time of water body, several reactions take place. As has been discussed above, BOD, DO, pH, alkalinity, hardness, and of course, temperature influence the chemical equilibria of reactions within the system.

The reactions in reservoirs--principally carbonate equilibrium--can be represented by the variation of an equilibrium constant, K. Thus (Langbien and Durum, 1967):

$$\frac{d(\ln K)}{dT} = \frac{E_a}{RT^2} \quad (51)$$

where

- T = absolute temperature
- E_a = activation energy
- R = gas constant.

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SECTION IV
ECOLOGICAL IMPACTS RESULTING
FROM RESERVOIR CONSTRUCTION

Ecology is concerned with all the organisms living in a habitat, the physical chemical characteristics of that habitat, and the processes which unite these two categories into a functioning system. It is a young science less than 100 years old and has not yet acquired the huge body of data about the environment nor reached the levels of sophistication in data analysis that older sciences have. Ecologists do have considerable data on many species and habitats, but they lack a detailed understanding of the processes which connect species and habitats together into stable, productive ecosystems. This lack of complete knowledge about the functioning of the ecosystem is reflected by the fact that few good measures of ecosystems currently exist, and those available are best used as modifiers of other parameters describing species or habitats. Obviously, it would be desirable to possess such a firm understanding of ecological relationships that environmental impacts could be quantitatively determined by FORMULAE. At present, this is not attainable; thus, emphasis is placed on empirical estimations based upon measured parameters.

Ideally, ecological impacts would be analyzed by establishing the change in biota and habitats resulting from a project. This entails a reference point from which change can be measured. This reference point might be determined from existing data or from measured data taken in the field. Monitoring programs would then be initiated to provide comparable data over time. Once these data are available, impact would be identified as the degree of change between commensurate units.

However, at this time, ecological impacts are typically predicated in two ways: (1) professional judgment, based upon a knowledge of the biota and habitat present, knowledge of the impending impact, results from similar studies, and common sense; and (2) a few simulation models based upon simplifying (and often unrealistic) assumptions and a knowledge of the biota and habitat being emulated. Before any impact prediction can be made, some

biotic and habitat measurements must be taken to reference the system being stressed.

The purpose of this section is to document various types of ecological impacts which may occur due to reservoir creation, and to provide guidance considerations to be used in the evaluation of environmental impact statements on proposed reservoir projects. Six areas of general impacts resulting from reservoir projects are first identified. Each of these general areas is then discussed in more detail, citing specific impacts that have or may occur in certain circumstances and situation-specific factors that may influence the magnitude or significance of impacts. These presentations of terrestrial and aquatic ecological impacts are followed by discussions of some important considerations in making baseline measurements of environmental conditions. A bibliography of literature on reservoir impacts completes the section.

GENERAL ECOLOGICAL IMPACT AREAS

The literature contains numerous references describing potential or historically experienced environmental impacts of reservoir creation on ecosystems. These references typically deal with site specific variables; therefore, a general statement attributing specific effects to all reservoir projects is scientifically unacceptable. However, six general ecological impact areas resulting from the creation of all reservoirs can be identified as follows.

Terrestrial Impacts

A Given Amount of Terrestrial Habitat Will be Destroyed by Inundation -

That portion of the terrestrial habitat located within the area of both the projected seasonal pool and most of the flood-pool will be totally destroyed as a result of reservoir creation. The amount of habitat that will be destroyed is determined by (1) purpose(s) of the reservoir, (2) reservoir design, and (3) topography of the region in which the reservoir

is located. Reservoir purpose(s) and regional topography determine reservoir design. The amount of habitat to be inundated is generally calculated after determining these three factors. Once these data points are established, a detailed topographic map is planimeted (at the operating water column height) to determine acreage to be inundated.

The Land/Water Interface Within the Impact Region Will Increase After Reservoir Formation -

As a result of both the seasonal and flood pools, the area of the land/water interface will increase upstream from the dam. The amount of increase can be calculated by planimeter methods from data derived from (1) purpose(s) of reservoir, (2) reservoir design, and (3) topography of the region in which the reservoir is located.

Two terrestrial habitats, the drawdown zone, discussed below, and the uninundated terrestrial habitat are influenced by the increase in the land/water interface. This influence is produced through modification of the physical environment, i.e., radiant energy increases, a larger interface for wind action, increased evapo-transpiration rates, etc, commonly called, collectively, the "edge" effect (Odum, 1970; Treshaw, 1970). Specific impacts are site unique and cannot be discussed in a general vein.

A New Habitat "The Drawdown Zone" Will be Created -

A release of water for hydroelectric power production, industrial or domestic water supplies, irrigation and flood control usually occurs throughout the year at most reservoirs. Water input seldom coincides with water output; thus changes in the lake volume occur. As a result of this fluctuation in water level, a belt of periodically inundated terrestrial habitat is formed. This phenomenon has been described as a "bathtub ring".

Periodic changes in water levels tend to restrict vegetation growth and establishment in the drawdown zone. Factors that influence

growth and establishment are (1) duration of flooding, (2) season in which inundation occurs, (3) sedimentation, and (4) species present within the drawdown zone.

Although an occasional inundation for a short period of time during the dormant or early spring season will not affect many tree species, some upland hardwoods will not tolerate even short-term inundation. Other species can withstand short periods of inundation if sedimentation does not occur. Seedlings can also withstand periodic inundation during the dormant season and even brief flooding during the growing season. However, if deposits of sand or silt are laid down (3" or more), the roots tend to be smothered.

Shrubby and herb-type vegetation may or may not vegetate a drawdown zone. This depends upon (1) duration of flooding, (2) season in which inundation occurs, (3) sedimentation rates, and (4) species present. As with the tree vegetation, inundation during the growing season will result in a die-back. Sedimentation tends to smother plant roots, and in many cases, inhibits seeds from germinating.

The absence of vegetation within the drawdown zones precludes much use by animal species. While drawdown is occurring, otters and raccoons will feed on benthos organisms exposed by the receding waters and some birds will utilize the drawdown zone for feeding.

Size of the new habitat is determined by topography of the lake body and purpose of the lake. Topography determines the surface of habitat formed by drawdown or inundation. Purpose determines the use(s) of the waterbody which, in turn, dictates the degree of volume change.

Acreage of new habitat is calculated by (1) determining the height of the drawdown pool, (2) planimentering the appropriate topographic line, (3) multiplying this distance by the height difference to the flood-pool, and (4) establishing acreage.

The relationship of the new habitat to the scenario of the lake ecosystem cannot be generalized. Each reservoir should be evaluated separately by comparing environmental survey data with monitored data.

Nutrient Input to the Downstream Terrestrial Environment Will Decrease Due to the Entrainment of Sediments Within the Impoundment -

Water flowing across agricultural lands, feedlots, forests, etc, is the most important mechanism in the transport of soil particles, plant residues, manure, and nutrients from the terrestrial environment to the aquatic environment. Streams, creeks, and rivers carry these deposits to other terrestrial areas and to the oceans.

The reservoir serves as a "sink" for sediments and nutrients carried by the waterbody being impounded. As a result, a portion of the input energy (nutrients, carbon and mineral soils, etc) normally received by the downstream terrestrial habitat is now held by the reservoir (Ortolano et al, 1973).

Definitive data on specific nutrients and on distance transported downstream are not generally available. However, sediment load or degree of sedimentation occurring within the reservoir is usually predicted in the process of reservoir designs. These data can be used to estimate the degree of nutrient entrapment. However, the magnitude of this phenomenon is site specific and gross statements should not be made.

The following equation is used to predict sediment load:

$$V_S = EQ_S$$

where V_S = volume of sediment storage per year

E = trap efficiency of reservoir

Q_S = volume of sediment which enters reservoir/year.

$$E = 1 - \frac{1}{1 + RC/W}$$

where C/W = reservoirs capacity (acre-feet) to watershed area (m_1^2)

R ranges from .046 to 1.0 with mean value .1

or

$$E = \frac{1}{.012 + .0102 C/I}$$

where C/I = reservoir capacity to annual inflow.

The sediment inflow Q_s is estimated from sediment transport studies or from actual sedimentation measurements from the waterbody to be impounded.

$$Q_s = f(D, V, S, P, \gamma, \mu, d, \gamma_s, q)$$

where D = flow depth

V = mean velocity

S = slope

P = density of fluid

γ = specific wt of water

μ = viscosity of water

d = particle diameter

γ_s = specific wt of particles

q = amount of water passing through.

Aquatic Impacts

A Lacustrine (Lake) Habitat Will Replace a Fluvial (Stream) Habitat -

The primary purpose of a reservoir is to provide a barrier to unrestricted drainage within a watershed. Thus, all dams serve to impound water at their upstream faces. Subsequent to impoundment, the former stream takes on more lake-like characteristics due to a variety of reasons, including (1) increase in depth, (2) increase in retention time, and (3) increase in land-water interface. The reach of a stream thus affected is equal to the length of the reservoir pool. The length of the pool is determined by the water level (ASL or AD), at any instant in time, in relation to the longitudinal profile of the stream. The pool length is then equal to

$$MP_2 - MP_1$$

where MP_2 = milepost of the stream at that location where the water level (ASL or AD) is equal to that which is maintained by the reservoir

MP_1 = milepost at the upstream face of the dam.

The area, depth, and volume of the pool can be determined planimetrically as described above. In some reservoirs, depending on purpose, size, location within the watershed, and discharge regime, pool dimensions are rather constant; in others (characterized by extensive water level fluctuations), dimensions are variable in time.

Due to impoundment, a stream reach becomes, to varying degrees, a lake. Whereas both are aquatic habitats, their ecological characteristics are different, predicated on different arrays of physical constraints. Current is much more of a controlling and limiting factor in streams. Air-water and land-water interfaces are more extensive in streams than lakes, leading to more uniform gas tensions and a more open ecosystem with a heterotrophic type of community metabolism.

Typically, compositional and functional aspects of stream and lake communities are somewhat different. Species diversity per unit area is usually higher in streams, due to the plethora of microhabitats available for utilization. Food webs in most streams are based upon (and dependent upon) continual input of allochthonous detritus (organic material from outside the water body), whereas lacustrine food webs are more closed, dependent instead on in situ (primary) production of organic substrates. Stream-dwelling organisms are generally more tolerant to thermal changes, but less tolerant to gas tension changes, than are lake-inhabiting organisms.

Due to these and other factors, the species composition and community function of a stream ecosystem will change if the stream is impounded. Some species will be excluded from the new ecosystem; others will occur in the new ecosystem which were not present in the old one. Evaluation of specific changes in species composition and community function must be done on a case-by-case basis, due to the large number of geographic and reservoir design variables involved. Some degree of prediction as to the nature of the change is possible, if the following information is known.

- (1) Species composition of the stream reach which will be impounded
- (2) Species composition of lakes which approximate the characteristics of the impoundment-to-be

- (3) Physical changes which will occur due to impoundment (sedimentation, retention time, stratification, dissolved gas tensions, thermal regimes, etc)
- (4) Tolerance of stream species to changes in physical characteristics which will be elicited by the impoundment-to-be
- (5) Any intentional species additions (e.g., fish stocking) to be included in the proposed action.

However, assessment of ecological change can only be accomplished ex post facto by comparing results of postimpoundment surveys with preimpoundment surveys. It should be remembered that postimpoundment characteristics will change in time, and, therefore, establishment of a rigid benchmark for survey periods is inappropriate.

The Stream Community Downstream of the Reservoir Outlet Will Change in an Indeterminant Manner -

Impoundment invariably changes the downstream flow regimen. The nature and extent of this alteration is a function of the discharge regime of the dam, the location of the dam within the watershed, and the upstream hydrological characteristics of the watershed. Alteration of the downstream flow regimen should be evaluated as a part of any impoundment project; this will involve the use of appropriate analytical techniques (see Leopold et al, 1964).

The effects of altered discharge regimens on downstream ecology must be evaluated on a case-by-case basis, since many variables enter into play. Historically, biologists involved in impoundment projects have attempted to determine the minimum quantity and quality of water which will "maintain" the stream resource. However, this approach has often led to maintenance of a mere vestige of the former downstream aquatic ecosystem. Discharge recommendations are often based on subjective judgment, without due consideration for the requirements of the organisms involved. Particularly inappropriate is the process by which attempts have been made to dignify judgmental decisions in connection with downstream flow regimens

vis-a-vis numerical quantification. Judgmental decisions must suffice in many cases but should not be disguised in a misleading form. Assumptions that a given percentage of former flow is the fundamental governing factor for maintenance of a given species or the stream's ecology as a whole are especially tenuous.

Prediction of the consequences of downstream flow regimen alterations requires a good deal of specific baseline information, and should be regarded as tenuous until after-the-fact investigations are made. Information required for evaluation of downstream impacts includes:

- (1) Baseline information on the flow regimen downstream of a proposed dam site
- (2) Itemization of the nature and extent of flow regimen changes which would be caused by construction and operation of a dam of specified design and size
- (3) Species composition (in time and space) of the downstream reach to be affected, to be investigated prior to initiation of construction
- (4) Location of special ecological features downstream (e.g., spawning areas, migration corridors, point source discharges)
- (5) Determination of tolerance of (3) and (4) to changes per (2).

The first four factors may be investigated prior to construction and operation of an impoundment. However, the longer-term aspects of (4) and (5), which are site specific, cannot be obtained from the literature and must await after-the-fact interpretation and evaluation. However, particular attention should be given before-the-fact to reservoirs proposed for geographical areas which are (1) in reaches of watersheds utilized for spawning by migratory organisms, (2) in reaches of watersheds which must be traversed by migratory organisms to upstream/downstream spawning areas, (3) in reaches of watersheds immediately upstream from coastal plain estuaries and/or marshes, (4) in reaches of watersheds utilized by migratory and/or resident waterfowl, and (5) in reaches of watersheds which are utilized by rare or endangered species.

TERRESTRIAL IMPACT ASSESSMENT CONSIDERATIONS

Little well-documented information on reservoir effects on terrestrial lands is available. Two reasons for this are: (1) reservoirs are permanent structures; thus, terrestrial lands which have been inundated for long periods of time are not available for study, and (2) reservoirs tend to be goal orientated; thus, some economic measure of effect (water for irrigation, transport, etc) has, in the past, been used to quantify impact. At present, however, environmental impacts are being considered in both the macro- and microenvironmental vein, which necessitates evaluating a project from both a site specific and regional viewpoint. The purpose of this section is to discuss specific impacts documented in Tables 6 through 11 and discuss factors which are of particular importance in controlling the nature and magnitude of these changes.

Inundation of Terrestrial Habitat

Inundation creates a catastrophic impact in that terrestrial habitat is converted to aquatic habitat. Any terrestrial land use formerly practiced on the inundated lands is, of course, no longer possible. Today, land is usually classified by what it is being used for, not by what it should be used for. Thus, few rules exist to guide the evaluator in making decisions concerning magnitude of impact. However, several factors can be considered which will enable one to make some estimates of environmental impact.

(1) What is the present land use in the inundated area? Are these lands considered "productive or marginal" in terms of food or fiber production? The inundation of marginal land would not have the secondary and tertiary effects that would result from inundation of productive farm and timber lands (foods, fiber, payrolls, taxes, etc).

(2) What is the present land use in the reservoir "region"? In many cases, the environmental effect of a reservoir is minimized when considering the region as a whole. The removal of terrestrial habitat by inundation may create new habitat below the reservoir due to stream

stabilization. Land use may change from marginal food and fiber production to recreational use. Power availability or flood control may open up new lands for more intensive management.

(3) What effects will the reservoir have on recreation and recreation-oriented industries? Evaluating these changes is not simple, nor are there any rules of thumb. Again, the suggested method is to evaluate effects as to (1) site specific and (2) regional. In many cases, local people welcome the idea of flood control, a new power source, or a channel to carry products to markets. However, the regional citizen, who uses marginal lands for hunting or a river for boating, tends to view reservoirs negatively.

(4) What effects will inundation have on the resident wildlife population? Some possibilities to consider are (1) decrease (or increase) in habitat diversity and carrying capacity, (2) displacement of wildlife due to construction and/or lake usage, (3) dissection of habitat and habitat isolation for animals with small home ranges, and (4) potential for migration routes being displaced or destroyed.

(5) Are there any rare or endangered species within the area to be inundated? Points to be considered for investigation are (1) displacement of local population, (2) increase or decrease in available habitat and carrying capacity, (3) increase or decrease in accessibility for collectors and hunters, and (4) potential for disturbance during construction.

These questions are only suggested as guidelines for developing questions concerning specific projects. Potential or historically documented examples of reservoir impacts to inundated terrestrial habitat are listed in Table 6.

Changes in the Land/Water Interface

Changes in the land/water interface, which is increased by reservoir creation, affect terrestrial habitats in two primary ways: changes increase the potential area for recreational use and changes increase the "edge effect" on terrestrial habitats.

TABLE 6. POTENTIAL TERRESTRIAL BIOLOGICAL IMPACTS ASSOCIATED WITH INUNDATION OF TERRESTRIAL HABITAT

Impact	Author(s)
Results in loss of productive lands including floodplain.	Blair, 1972 AED-Louisville, 1971 Bureau, 1972 TVA, 1972 AED-Huntington, 1972 Ortolano et al, 1973 AED-Savannah, 1972
Displaces natural wildlife populations.	Bureau, 1972 AED-Savannah, 1972
Changes available riparian vegetation habitat.	Ortolano et al, 1973 Symons, 1969
Removes possible link in food chain of animals such as black bear and bald eagle which depend on migrating salmon for a critical-time food supply.	Arend, 1969 Hynes, 1970
Interrupts migration routes of animals.	U.S. Senate, 1960
Loss of spring and fall forage for elk, moose, and deer.	Bureau, 1972
Fluctuation results in large barren areas, separates vegetation from water margin, and opens new terrestrial habitat.	Jackson, 1966 Arend, 1969
Forms localized marshes or swamps.	Berkowitz, 1971 Laglear, 1971
Increases aquatic growth at reservoir edges.	California, 1970 Ortolano et al, 1973 Wistendahl and Lewis, 1972
Results in damage by ice, debris, and fluctuating water level limiting shoreline tree size.	Wistendahl and Lewis, 1972
Controls nuisance plant growth.	California, 1970 Estes, 1972

Lake surfaces provide access to land areas which were isolated before reservoir construction. This ease of access presents problems which are indirect results of reservoir formation. People may displace wildlife, destroy plant life, and create erosion problems around lake shores. The reviewer should ask himself: (1) are there any fragile plant or animal populations subject to disruption from boating or lakeshore activities, and (2) are there shoreline areas where human activity could result in erosion problems? The "edge effect" (Odum 1970; Treshaw 1970) is the summation of changes in the physical environment which result when the terrestrial canopy is broken. This break results in increased radiation (sunlight) levels, increased evapotranspiration rates, and furnishes a larger surface area influenced by wind. The major consequence of these changes is that dominant canopy habitat is replaced with edge habitat. Due to higher energy input (solar radiation) and less competition for moisture (depending on topography), edge communities are much more productive. Thus, carrying capacity for some organisms (deer, raccoon, songbirds, rabbits) is actually increased.

When considering impacts due to edge effect, the reviewer should consider such questions as

(1) What kind of "edge" will result from reservoir formation? Narrow, deep lakes with fluctuating water levels are not conducive to good "edge" habitat because small fluctuations in water levels result in habitat destruction and erosion problems. Reservoirs with gentle slopes and relatively stable water levels are conducive to good "edge" habitat formation.

(2) What type of recreational use will the lakeshore receive? Heavy use by campers and "day users" can result in shoreline degradation without proper management.

(3) What type of plant communities are expected to emerge along the lake shore? Slope angle plays a dominant role in determining community type and success. Wistendahl et al (1972), found that slopes above 20 percent tended to erode rapidly, thus preventing plant establishment. On slopes 20 percent and under, slight erosion took place and a potential for natural revegetation was present.

(4) What is the potential for bank erosion and what will be the effects? An eroding shoreline precludes the establishment of stable plant

communities. The effect of erosion on aquatic systems is discussed in the aquatic section below.

The formation of an "edge" habitat offers several possibilities when considering environmental impacts. Examples of actual and potential impacts are shown in Table 7. The questions and statements listed above are only suggested guidelines for concepts that should be addressed.

Creation of a Drawdown Habitat

As water input seldom coincides with water output, changes in reservoir volume occur; the magnitude of that change is dependent upon the purpose(s) of the reservoir.

Terrestrial vegetation will not tolerate sustained inundation particularly during the growing season. Inundation of the plant canopy blocks gaseous exchange and photosynthesis in the leaf, whereas inundation of the stem prevents CO_2 - O_2 exchange in the soil.

Several concepts should be addressed when considering the potential for drawdown habitat formation.

(1) What is the intended use of the reservoir? Reservoirs designed for channel maintenance or water supply seldom have large volume changes; thus, the potential for creating a drawdown zone is slight. Flood control reservoirs, however, do have seasonal fluctuations in water levels large enough to form drawdown zones.

(2) What is the topography surrounding the lake? (Steep narrow-sided lakes do not reflect the volume change that would occur in relatively flat topography.

(3) What time of the year is drawdown anticipated? Many plant species can withstand short periods of stem inundation (if excessive siltation doesn't occur) during their dormant periods. However, inundation during the growing season will result in death for most plants. Flooding effect on southern forests is discussed by Broadfoot and Willinton (1973).

(4) What is the erosion potential during drawdown? Erosion during drawdown occurs through two mechanisms: (1) rainfall and (2) wave action. In flood control reservoirs, drawdown occurs just before the annual

**TABLE 7. POTENTIAL TERRESTRIAL BIOLOGICAL IMPACTS ASSOCIATED WITH A
CHANGE IN THE LAND/WATER INTERFACE**

Impact	Author(s)
Changes available riparian vegetation habitat.	Ortolano et al, 1973 Symons, 1969
Stimulates growth of normally suppressed organisms, possibly of detriment to others.	Ortolano et al, 1973
Interrupts migration routes of animals.	U.S. Senate, 1960
Increases land/water interface causing appearance of new dominants and population complexes.	Berkowitz, 1971
Fluctuation results in large barren areas, separates vegetation from water margin, and opens new terrestrial habitat.	Jackson, 1966 Arend, 1969
Forms localized marshes or swamps.	Berkowitz, 1971 Laglear, 1971
Increases aquatic growth at reservoir edges.	California, 1970 Ortolano et al, 1973 Wistendahl and Lewis, 1972
Results in damage by ice, debris, and fluctuating water level limiting shoreline tree size.	Wistendahl and Lewis, 1972
Restricts shoreline species often to willow and silver maple which survive by frequent and successful root sproutings.	Wistendahl and Lewis, 1972

spring rains or snow melt occurs. During this time, wave action can severely erode unprotected banks. Likewise, during the "fill-up" period, heavy rains will erode unprotected banks.

Table 8 lists examples of potential site specific impacts due to drawdown.

Decreased Nutrient Inputs to the Downstream Terrestrial Environment

Nutrient input from stream or river overflow is an important source of energy to the adjacent terrestrial habitat. However, when a dam is built, the reservoir serves as a "sink" for sediments and nutrients carried by the waterbody being impounded.

Several concepts should be considered in evaluating this impact.

How will the riparian habitat be affected? Stream overflow plays several roles in determining the structure of riparian vegetation: it furnishes nutrients, builds new land by sediment deposition, acts as a selection mechanism in species composition, removes brush and other organic debris, and maintains soil moisture levels.

Will a reduced nutrient input, along with stabilized flow, create a new habitat? As stated in above, the overflow selects for certain plants in that sediment deposition and periodic inundation establish a unique environment suitable for certain species. When sediment deposition and periodic overflow are curtailed, the plant environment changes. This increases the potential for the introduction of new species, a situation which could result in a new habitat type.

Examples of potential impacts resulting from a nutrient reduction to the downstream terrestrial habitat are listed in Table 9.

AQUATIC IMPACT ASSESSMENT CONSIDERATIONS

A considerable amount of information on the ecology of reservoirs is available. Limnologists throughout the world have been attracted to man-made impoundments as outdoor laboratories. These impoundments represent

**TABLE 8. POTENTIAL TERRESTRIAL BIOLOGICAL IMPACTS ASSOCIATED WITH THE
CREATION OF A DRAWDOWN HABITAT**

Impact	Author(s)
Changes available riparian vegetation habitat.	Ortolano et al, 1973 Symons, 1969
Stimulates shoreline erosion.	Wistendahl and Lewis, 1972
Fluctuation results in large barren areas, separates vegetation from water margin, and opens new terrestrial habitat.	Jackson, 1966 Arend, 1969
Increases aquatic growth at reservoir edges.	California, 1970 Ortolano et al, 1973 Wistendahl and Lewis, 1972
Results in damage by ice, debris, and fluctuating water level limiting shoreline tree size.	Wistendahl and Lewis, 1972
Restricts shoreline species often to willow and silver maple which survive by frequent and successful root sproutings.	Wistendahl and Lewis, 1972

**TABLE 9. POTENTIAL TERRESTRIAL BIOLOGICAL IMPACTS ASSOCIATED WITH A
REDUCTION OF NUTRIENTS TO THE DOWNSTREAM TERRESTRIAL HABITAT**

Impact	Author(s)
Reduces natural fertilization from flooding.	Ortolano et al, 1973
Changes available riparian vegetation habitat.	Ortolano et al, 1973 Symons, 1969
Stimulates growth of normally suppressed organisms, possibly to the detriment of others.	Ortolano et al, 1973 Wilson & Bossert, 1971
Loss of spring and fall forage for elk, moose, and deer.	Bureau, 1972
Fluctuation results in large barren areas, separates vegetation from water margin, and opens new terrestrial habitat.	Jackson, 1966 Arend, 1969
Increases aquatic growth at reservoir edges.	California, 1970 Ortolano et al, 1973 Wistendahl and Lewis, 1972

recent lacustrine environments and offer the opportunity for understanding limnological processes not necessarily typical of some of the natural lakes of the world.

Reservoirs are constructed for one or more of a variety of purposes, including flood control, hydroelectric power, water supply, and/or recreation. Depending on the design of a reservoir and the environmental circumstances in which it is constructed, the reservoir may or may not differ appreciably from other lakes in the same geographical region. However, reservoirs in all cases differ physically from the streams from which they arise. These physical differences cause changes in the aquatic ecosystem in the impounded reach of the stream and usually downstream from the dam face as well. Some of the specific changes which occur are documented in Tables 10 and 11.

This section categorizes various types of ecological changes coincident with surface water impoundment and discusses factors which are of particular importance in controlling the nature and extent of these changes.

Eutrophication

One of the fundamental "building blocks" of any living system is carbon which is the major constituent of organic matter. Autotrophic processes are those involving in situ production of organic matter. Autotrophic processes, on the other hand, involve influx of organic materials into the system in question. In this context there are four general types of lakes: dystrophic, mixotrophic, oligotrophic, and eutrophic. Dystrophic lakes have large amounts of allotrophic organic material influx relative to autotrophic production. Oligotrophic lakes and mixotrophic lakes are characterized by small and large amounts of total organic matter production and influx, respectively. Eutrophic lakes, on the other hand, are characterized by large amounts of autotrophic organic material production relative to allotrophic influx.

The magnitude of autotrophy in a lake is a direct function of primary productivity occurring therein, since photosynthesis is the chief means by which organic material is initially produced. Whereas, there is

TABLE 10. POTENTIAL AQUATIC BIOLOGICAL IMPACTS ASSOCIATED
WITH RESERVOIR POOL FORMATION

Impact	Author(s)
Requires several years for the system to attain stability.	Hynes, 1970
Increases detention time associated with reservoirs increasing the extent of bacterial decay over a given length of watercourse.	Kittrell and Furari, 1963
Reduces overall quality of the environment from insufficient dissolved oxygen.	Ortolano et al, 1973 Anonymous, 1967
Increases rate of deoxygenation caused by decomposition of inundated vegetation and/or organic debris during first year.	Jackson, 1966
Permits decomposition of the suspended load on a reservoir bottom to develop a readily available pool of minerals and nutrients causing water quality deterioration.	Ortolano et al, 1973
Displaces natural river habitat and organisms.	Wistendahl and Lewis, 1972
Alters fish distribution and populations from extensive enrichment.	Ortolano et al, 1973
Results in possible overpopulation with rough fish.	Findlay, 1972 Jackson, 1966
Changes due to hypoliminal releases from lack of dissolved oxygen.	Symons, 1969
Affects clam beds.	Berkowitz, 1971
Alters success of freshwater mussel beds.	Tennessee Game, 1972 Hynes, 1970
Stimulates growth of normally suppressed organisms, possibly to detriment of others.	Ortolano et al, 1973 Wilson & Bossert, 1971
Creates a rich organic, but temporary, food supply for insects larvae and detrital invertebrates.	California, 1971 Jackson, 1966
Drops fertility levels after first few years becoming more conducive to successful reproduction to competitive species.	Jackson, 1966
Reduction in cold water fisheries.	TVA, 1972 Bureau, 1972

TABLE 10 (Continued)

Impact	Author(s)
Increased plankton and benthic habitats.	Hynes, 1970
Interrupts migration routes of fishes.	U.S. Senate, 1960
Changes host parasite relationships of organisms of the region.	Becker, 1971 Waddy, 1966 Houghton, 1966
Increased parasitism in bass resulting in decline of sport fishing.	Becker, 1971
Increases aquatic growth at reservoir edges.	California, 1970 Ortolano et al, 1973 Wistendahl and Lewis, 1972
Changes general fishing success.	Estes, 1972 Jackson, 1966 Baren and Howlett, 1971
Affects fish spawning (sediment, cover, temperature).	Ortolano et al, 1973 Fraser, 1972a and b Baren and Howlett, 1971 Estes, 1972 Hynes, 1970
Stimulates downward movement of species to deeper, open waters.	Jackson, 1966

TABLE 11. POTENTIAL AQUATIC BIOLOGICAL IMPACTS ASSOCIATED
WITH ALTERATION OF DOWNSTREAM FLOW REGIMEN

Impact	Author(s)
Reduces overall quality of the environment from insufficient dissolved oxygen.	Ortolano et al, 1973 Anonymous, 1967
Displaces natural river habitat and organisms.	Wistendahl and Lewis, 1972
Changes due to hypolimnial releases from lack of dissolved oxygen.	Symons, 1969
Reduces natural fertilization from flooding.	Ortolano et al, 1973
Reduces flow of food downstream from lake sedimentation.	Findlay, 1972 Jackson, 1966
Changes in thermal regime cause reduction of benthic fauna downstream.	Lehmkuhl, 1972
Reduces freshwater flowing into estuaries.	Blair, 1972
Alters success of freshwater mussel beds.	Tennessee Game, 1972 Hynes, 1970
Stimulates growth of normally suppressed organisms, possibly to detriment of others.	Ortolano et al, 1973 Wilson & Bossert, 1971
Modifies spawning areas downstream.	U.S. Senate, 1960 Ortolano et al, 1973
Increases natural hatchery success due to altered flow variability.	AED-Portland, 1971
May reduce cold water species populations from decreased flow levels.	U.S. Senate, 1960
May benefit cold water species environment with downstream water warmer in winter, cooler in summer	Wirth, 1970 Symons, 1961 Ortolano et al, 1973
Reduction in cold water fisheries.	TVA, 1972 Bureau, 1972
Interrupts fish migration.	Hynes, 1970 Arend, 1969 Major, 1972

TABLE 11 (Continued)

Impact	Author(s)
Changes general fishing success.	Estes, 1972. Jackson, 1966 Baren and Howlett, 1971
Affects fish spawning (sediment, cover, temperature).	Ortolano et al, 1973 Fraser, 1972a and b Baren and Howlett, 1971 Estes, 1972 Hynes, 1970

no definitive breakoff between primary productivity rate and trophic status, Rhode (1969) suggests that there are loose-knit ranges that can be generally considered as benchmarks. These are listed in Table 12.

TABLE 12. RELATIONSHIP BETWEEN TROPHIC STATUS AND PRIMARY PRODUCTIVITY (RHODE, 1969)

Primary	Productivity	Oligotrophic	Eutrophic	
			Natural	Polluted
Mean growing	Season rates	30-100	300-1000	1500-3000 mgC/M ² /day
Annual rates		7-25	75-250	350-700 gC/m ² /year

Almost all lakes, whether natural or man made, undergo a natural succession toward eutrophy. Various perturbations can increase the rate at which a lake becomes eutrophic, the most important of which is nutrient influx, particularly with regard to labile forms of phosphorus and/or nitrogen.

As an aquatic ecosystem becomes more productive in response to nutrient influx, a number of changes often occur. Water transparency decreases, oscillations of dissolved gas concentrations become greater, producer and consumer biomasses increase, species diversity generally decreases, and mean weights of individuals comprising consumer populations generally decrease. In dimictic (two turnover periods annually) and warm monomictic (one turnover annually) lakes characteristic of the United States, problems often result during periods of thermal stratification, particularly in the hypolimnion. In extreme cases of hypolimnetic deoxygenation, water quality deteriorates, anaerobic decomposition may produce odorous smells at the lake's surface, and fish kills due to suffocation may occur.

Eutrophication problems are not unique to reservoirs, but surface water impoundment usually presents a unique set of circumstances with respect to eutrophication. Newly created reservoirs often undergo an initial stage of relatively high rates of autochthonous production, due to nutrients released from decomposing terrestrial vegetation and soils which have been subjected to inundation. This case would not be true for a barren mountain

valley subjected to impoundment, but is true for the majority of impoundments which inundate extensive amounts of terrestrial vegetation. Most well-designed and appropriately located reservoirs become less eutrophic after the first 3 or 4 years of their existence, as nutrients derived from inundated vegetation are transported downstream of the dam face and hence outside of the reservoir ecosystem. Many variables are involved, particularly the morphometry of the lake and its retention time. Lakes of relatively low-mean depths and high-surface area/volume ratios generally require more time for natural eutrophication abatement, as is the case for lakes with long retention times. However, the most important set of variables concerning the future trophic fate of an impoundment are those influencing nutrient influx into the lake basin from other points within the watershed.

In many situations where nutrient influx from within the watershed is appreciable and continuous through time, a reservoir will generally tend to become more eutrophic through time rather than clear up of its own accord. This is because a reservoir tends to trap nutrients which formerly passed down a free-flowing stream.

Presently, a considerable amount of controversy prevails as to which types of plant growth nutrients are critical to the control of eutrophication in reservoirs. Generally, phosphorus appears to be a key limiting nutrient, although nitrogen, carbon, and/or silicon may be in critical supply in selected reservoirs. Thus, nutrient limiting factors must be evaluated on a case-by-case basis.

Methods for forecasting the nature and extent of eutrophication of newly constructed reservoirs are neither specific nor well developed. However, a variety of factors should be taken into account in evaluating this potential. These are outlined below, and requisite information should be considered in reservoir planning procedures.

- (1) What is the nature and extent of the vegetation in the land area to be inundated? (Heavily fertilized soils will produce more extensive initial phases of algal growth than will barren or forested areas.)

- (2) What will the morphometry of the new lake basin be like? (Lakes with high surface area/volume ratios have a greater potential for eutrophication than deeper, steep-sided ones.)
- (3) What will the retention time (the reciprocal of "throughput") of the impoundment be like? (Impoundments with long retention times will require more time to clear up after their inception than will impoundments with rapid throughput.)
- (4) Will the impoundment undergo thermal stratification on a regular yearly basis? What will the duration of the stable (thermocline present) stratified period be? (Hypolimnetic water quality and fisheries may be susceptible to deterioration under stratified conditions.)
- (5) What is the nature of the general land use pattern in the immediate vicinity of the impoundment? (High intensity agricultural practices and/or feedlot operations may contribute extensive and continual nutrient burdens to the reservoir pool, thus accelerating eutrophication.)
- (6) What is the nature of influent water quality from streams entering the reservoir pool? (Large and continual nutrient burdens may occur in the reservoir pool due to sewage and/or industrial wastes. On the other hand, some types of toxic industrial wastes may serve to inhibit algal growth and thus act as a deterrent to eutrophication.)
- (7) What types of eutrophication control measures are included in the proposed action? (Artificial destratification via aeration; chemical precipitation of phosphates with aluminum sulphate, etc; and addition of copper sulphate all serve to improve one or more aspects of water quality, but may produce adverse effects as well, e.g., reduction in fisheries and/or potability.)

- (8) Are there reservoirs in the general vicinity (preferably the same watershed of a proposed reservoir in question) which presently exist, such that comparative deduction can be utilized? (Examination of the trophic status of surface water impoundments under similar conditions may provide valuable insight into the fate of a proposed impoundment.)
- (9) What is the primary use to which the impoundment will be put? (Most reservoirs are in part justified as multi-purpose, but are designed primarily to fulfill a particular purpose, e.g., flood control, hydroelectric, or water supply. The implications of eutrophication with respect to intended reservoir usage are substantially different. The potentially adverse effects of eutrophication would be greatest in reservoirs intended for water supply and would be of significance to recreational usage, particularly sport fishing, as well.)
- (10) Are there projected land use changes for the reservoir area, once created, or upstream or major tributaries which could have a significant future bearing on aforementioned influential factors?
- (11) What is the nature of the monitoring program designed to assess the nature, extent, and effects of eutrophication in the proposed reservoir? (A comprehensive monitoring program will include provision for measurement of primary productivity, phytoplankton associations, nutrient budgets (N and P), hypolimnetic oxygen deficit, and sediment redox potential. It will also include provision for detection of appropriate indicator organisms, fish composition, fish kills, and plankton blooms.)

These guidelines are suggested for use in a general manner in order to evaluate the comprehensiveness of environmental reports and environmental impact statements pertaining to proposed reservoir construction operations, and subsequent significance of eutrophication factors. A good

deal of technical literature pertaining to many aspects of eutrophication is readily available and should be consulted in the event specific information is desired for timely evaluation of environmental impact statements. Comprehensive treatment of the subject of eutrophication under single cover is provided by NAS (1969) and Vollenweider (1970a). Detailed information on a variety of technical facets of eutrophication can be readily screened via several bibliographic abstract sources; most useful are Vollenweider (1970b) and the University of Wisconsin Water Resource Center's bimonthly eutrophication abstracts (obtainable at no charge from UWWRC, 1324 West Dayton, Madison, Wisconsin 53706).

Sedimentation

When a stream is impounded to form a reservoir, its longitudinal profile is changed. Specifically, the profile is reduced in slope over a localized reach of the stream channel. This typically results in profound alteration of the substratum, both upstream and downstream of the dam face. Upstream of the dam face a relatively quiescent pool replaces a more turbulent flow regime. Since the ability of an aqueous system to carry in suspension particles of a given size range is directly related to the magnitude of turbulent flow (e.g., measured in terms of Reynolds number), large portions of suspended sediments settle out under quiescent conditions. When this occurs in a newly created impoundment, changes in substratum characteristics occur. Relatively small-sized particles cover the former stream substratum consisting of larger sized particles.

The change in the physical characteristics of the substratum underwrites extensive alteration in benthic composition. Species depending upon running water for food supply and hard attachment surfaces for position maintenance (e.g., attached algae, stoneflies, caddis flies, several species of mayflies, etc) are replaced by organisms which typically live "in" the substratum rather than "on" it (e.g., oligochaete worms, dipteran larvae, and rooted vegetation in littoral zones). Also, alteration of benthic composition obviously affects species dependent on benthic organisms as a food source, such as some species of fish and birds. Species diversity of

the benthos of an impounded pool is usually substantially lower than in its formerly unimpounded, free-flowing status.

The pattern of sedimentation in reservoirs is usually not uniform. In situations where influent tributary flows are extensive, deltas typically form at their mouths. In reservoirs where influent streams are relatively sluggish, sediment deposition is usually maximal in the most quiescent region(s) of the reservoir pool, oftentimes near the dam face itself. Sedimentation patterns are greatly influenced by the morphometry of the basin and the degree of water level fluctuation in the reservoir pool (Borland, 1971).

Sedimentation rates are also extremely variable when considering an array of reservoirs. Key variables are loading rates of washloads and bedloads, particle size distributions of washloads and bedloads, morphometry of the impoundment's basin, the retention time of the pool, and the nature of the upstream watershed. Instances of rapid reservoir sedimentation and factors underlying this phenomenon are discussed by Langbein and Hoyt (1959) and Allen (1972).

Aggradation can also occur in both upstream tributaries and downstream from the reservoir due to altered flow regimes. Sediment islands thus formed change portions of stream channels from aquatic to terrestrial habitats. The resultant decrease in stream capacity may be sufficient to cause flooding of adjacent terrestrial habitats on a regular basis. In some cases, above-datum emergent deltas and islands may become vegetated leading to further increase in size. In others, erosion of these depository forms can lead to intermittent reductions in water quality in or downstream from the reservoir. In addition to sedimentation rates, sedimentation patterns can have significant effects on the ecology of a reservoir and upstream and downstream areas. In reservoir planning and in the evaluation of existing or proposed reservoir projects, various factors pertaining to sedimentation rates and patterns should be considered:

- (1) What is the nature of washload and bedload loading rates into the impoundment? (High loading rates should be regarded as having significant potential for eliciting extensive sedimentation.)

- (2) What are the particle size distributions of the washload and bedload, and how do they relate to turbulence for suspension requirements? (Virtually all bedload from influent tributaries will settle out in a reservoir. Those fractions of the washload which are not clay-like in constituency will also usually settle out. Extremely small-sized particles such as clays will usually remain in suspension for long periods of time even under extremely quiescent conditions.)
- (3) What fractions of the washload and bedload are organic detrital material? (Heavy loading of detritus will promote extensive decomposition, will provide a food source for detritovores, and will provide nutrients in most cases for enhancement of algal growth. Lakes subjected to appreciable detritus loading are usually characterized by high benthic productivity in deeper regions of their basins.)
- (4) What is the nature of the bathymetry of the reservoir pool at the time of its inception? (Initially, sedimentation is most likely to be most extensive in deep holes, protected (from wind) bays, at the dam face, and at the mouths of influent streams if they are not sluggish streams.)
- (5) Are there natural lakes, reservoirs, or check dams upstream of the impoundment in question? (These will cause sediment loading to be appreciably reduced in that they themselves act as sediment traps.)
- (6) What is the nature of the terrain and soils surrounding the reservoir? (High topographic relief and/or absence of well-rooted vegetation could lead to appreciable erosion under periods of extensive rainfall, thus vastly increasing sedimentation rates.)
- (7) Will water level in the impoundment be constant or fluctuating? (Extensive water level changes will tend to reduce

overall sedimentation rates, but will cause sediments to be deposited primarily at mouths of influent streams and in the deeper portions of the lake. Fluctuating water levels will also tend to inhibit the formation of littoral-rooted vegetation which acts as a sediment trap due to quiescent conditions which it produces.)

- (8) What types of benthic organisms inhabit similar lakes in the same region, particularly in the same watershed? (Benthic species composition is oftentimes quite similar in related and/or interconnected lakes.)
- (9) What are the anticipated trophic characteristics of the impoundment? (Eutrophication will elicit a reduction in benthic species diversity in the substratum, particularly during the summer months. Of those species remaining, production and decomposition rates will be appreciably higher than under oligotrophic conditions.)
- (10) Are natural stream discharge regimes rather uniform? Will discharge regimes from the impoundment be appreciably reduced? (These factors will be important determinants of upstream and/or downstream aggradation. Delta and island formation will change portions of stream channels from aquatic habitats to terrestrial habitats.)
- (11) What is the nature of the monitoring program designed to assess the nature, extent, and effects of sedimentation in the reservoir? (A comprehensive monitoring program will include provision for measurement of bathymetry, benthos species composition, particle size distribution of the deposited sediments, and sedimentation rates at various locations within the reservoir pool.)

A substantial amount of technical literature pertaining to sedimentation in reservoirs and its effects upon reservoir ecology is available. In addition to the aforementioned guidelines, pertinent literature dealing with specifics on sedimentation and its effects in reservoirs should be consulted in order to render reliable evaluations of proposed or existing

impoundment projects. Einstein (1968, 1972), Harrison (1953), Gottschalk (1964), and Borland (1971) provide generalized information on determination of reservoir sedimentation patterns and rates. Burris (1954), Fillion (1967), Nursall (1952), Oshegova (1962), Solokova (1963), and Peterson and Fernando (1970) provide information on benthic colonization of reservoirs which have had different sedimentation patterns. For those wishing or needing to further pursue technical aspects of sedimentation and its ecological effects, annotated bibliographies of domestic and foreign literature on sedimentation should be consulted. These are updated periodically by, and are available from, the U.S. Clearinghouse for Federal Scientific and Technical Information, Washington, D.C.

Thermal Stratification

When a reach of a stream is impounded, a variety of physical changes occurs, both directly and indirectly. One of the most important of these changes involves alteration of the thermal regime of the new water body. These alterations are brought about due to greater depth and reduction in the surface area/volume ratio coincident with impoundment of a stream. Many reservoirs exhibit a trait uncharacteristic of rivers from which they were derived, that of thermal stratification during the summer months. Thermal stratification results in the formation of two or more discreet zones within the reservoir pool, each behaving in large part independently of the other(s). Under stratified conditions, the "epilimnion" (top lake) is relatively warm and well mixed due to wind and/or tributary-derived energy and the "hypolimnion" (bottom lake) is relatively cold and stagnant. These two portions of the reservoir are separated by a "thermocline" (zone of rapid temperature decrease with respect to depth) which may be thick enough to constitute a rather arbitrarily defined "metalimnion" or middle-lake. The different stratas' integrities are maintained by differences in density attributable to differences in temperature. Hutchinson (1957) and Kittrel (1965) provide detailed information on the mechanisms underlying and regulating the nature and extent of thermal stratification. Discussion of forecasting techniques for thermal stratification patterns in newly

created impoundments is provided in the Water Quality section of this report.

The significance of thermal stratification to reservoir ecology is multifaceted; it provides an additional factor in habitat differentiation, and it often provokes a variety of changes in physical and chemical characteristics which in turn influence the ecological characteristics of the reservoir. Among these, generally the most important factor is that of the virtual isolation of the hypolimnion from surficial influences. In its isolated condition, if oxygen demand of sediments or suspended organics is extensive, dissolved oxygen concentrations in the hypolimnion may be appreciably reduced. Under these conditions, species inhabiting the hypolimnia of such lakes are limited to those which are tolerant of low oxygen concentrations; species diversity usually decreases as dissolved oxygen concentrations become low. In addition, reduced oxygen tension can have profound effects on sediment chemistry and consequent cycling of inorganic materials within the water column, many of which influence biological growth, especially nutrient releases which can contribute to eutrophication. Stratification can also lead to influent waters forming density currents at discrete levels within the lake. In summer time, these usually take the form of surface density currents since influent waters are generally warmer than those of the hypolimnion. Depending upon reservoirs discharge design, this can be of importance in determining residence time of incoming waters and consequently, the waste assimilative capacity of the reservoir.

A variety of factors should be taken into account in evaluating the nature and extent of thermal stratification in newly created or proposed reservoirs and the implications of stratification to reservoir ecology. These include

- (1) Is nutrient loading such that the reservoir is likely to become eutrophic on a long-term basis? (If so, extensive oxygen depletion in the hypolimnion can be anticipated during the period of stable stratification.)
- (2) Is detritus loading such that large amounts of detrital material will be present in the sediments? (This, too,

may cause extensive hypolimnetic oxygen depletion during stratified periods.)

- (3) Are fish stocking plans for recreational purposes consistent with anticipated hypolimnetic oxygen demands? (Warm water species should be utilized in situations where appreciable hypolimnetic oxygen depletion is anticipated.)
- (4) What is the proposed discharge regimen? (Reservoir discharge from a deoxygenated hypolimnion will be cold and low in dissolved oxygen concentration unless artificial aeration (e.g., raceways, turbine aerators, etc) is employed. This will instigate a localized stress in the stream ecosystem immediately downstream from the dam face.)
- (5) Are there industrial and/or agricultural discharges into the reservoir via influent streams? If so, how do stream temperatures compare with reservoir temperatures during stratified periods? (This information is necessary in order to evaluate the potential for density currents and consequent reduced assimilative capacity of the reservoir.)
- (6) Does the monitoring program include provision for regular measurement of temperature in the water column of the lake? (This information can be used to determine the duration of thermal stratification and the stability of the reservoir during stratified periods; it can also be used to indicate at what periods of the year vertical mixing occurs.)

Comprehensive technical treatments of thermal stratification and its significance in specific reservoirs are provided by Elder (1968) and Symons (1969). These should be consulted for more detailed technical information. Also see Knight (1965) and Krenkel, et al (1968), for additional information pertaining to the effects of thermal stratification on reservoir waste assimilative capacity and downstream water quality.

Dissolved Oxygen

In addition to being one of the most important water quality variables in reservoirs, dissolved oxygen levels and their fluctuations play an exceedingly important role in determining the ecological characteristics of reservoirs. Since dissolved oxygen concentrations in reservoirs can vary from zero to supersaturation, a wide variety of microhabitats are available to species which can capitalize on the immediate situation. For example, game fish are typically intolerant of oxygen concentrations less than 3-4 mg/l. On the other hand, many types of rough fish (e.g., carp, suckers, etc) apparently thrive under such conditions.

Dissolved oxygen concentrations in reservoirs vary both seasonably and spatially, and are intimately related to many other factors operating within the reservoir, such as temperature, nutrient loading, organic loading, sediment chemistry, and degree and type of biological activity. Dissolved oxygen enters a reservoir primarily by diffusion across the air-water interface and by algal photosynthesis. Diffusion rates are related to surface area, wind velocity, air temperature, water temperature, and most important, turbulence (Fair et al, 1968). Photosynthetic production rates are related to algal and/or submergent vegetation, standing crops, temperature, light intensity, nutrients, and available carbon dioxide. Dissolved oxygen is utilized by biological respiration and autoxidation of both organic and inorganic materials. Resultant dissolved oxygen concentrations in the water column reflect the relative balance of production and utilization processes.

Distribution of dissolved oxygen within a reservoir is influenced by the mixing pattern of the reservoir pool. During periods of thermal stratification, dissolved oxygen concentration in the hypolimnion is apt to become quite low if hypolimnetic oxygen demand is high. This is of important significance to hypolimnetic biological activity and sediment chemistry. When dissolved oxygen concentrations decrease to near zero (to the extent that the oxidation-reduction potential of the sediment surface is negative), reducing conditions prevail. Insoluble oxidized states of iron (Fe_2O_3), Manganese (Mn_2O_3), and Phosphorus (FePO_4) are reduced,

resulting in releases of soluble states of these algal growth nutrients, thus further contributing to eutrophication.

Various factors should be considered in evaluating the potential for adverse dissolved oxygen reduction in reservoirs. In addition to those to be considered with regard to eutrophication potential (see above), the following should be considered:

- (1) What is the nature of present or anticipated loading rates of organic materials into the reservoir? (All of these will contribute to oxygen demand, in addition to in situ respiration.)
- (2) What is the predicted depth of the thermocline? (This may determine the extent of the "usable" portion of the impoundment during stratified periods.)
- (3) Will existing vegetation and woody debris in the basin be removed prior to filling? (This will reduce initial oxygen demand.)
- (4) Is the woody vegetation surrounding the reservoir deciduous or coniferous? (Deciduous leaf litter can contribute extensive oxygen demand on a long-term basis.)
- (5) What is the intended use of the reservoir? (Extensive hypolimnetic oxygen demand can serve to reduce water quality and limit fishery potential. Hence, reservoirs planned for water supply and/or recreational fishing would present intended use inadequacies in the event of intensive oxygen demand.)
- (6) What is the nature of the monitoring program designed to determine dissolved oxygen concentrations in the reservoir? (A comprehensive monitoring program should include provision for regular measurement of dissolved oxygen at the surface, middle, and bottom of the water column and should include provision for summer measurement of sediment redox potential and limiting algal nutrients liberated from the sediment.)

- (7) What is the proposed downstream discharge regimen and penstock location of the dam? (Hypolimnetic discharge, if not aerated, can cause depleted dissolved oxygen concentrations for a localized distance downstream. This will result in exclusion of species intolerant of low dissolved oxygen concentrations from this reach of the stream.)

See Public Health Service (1965) and Symons (1969) for additional technical information pertaining to the determination, influence, and implications of dissolved oxygen concentrations in reservoirs and their downstream discharges.

Coliform Bacteria

Not all members of the coliform group of gram-negative bacteria are pathogenic. However, total coliform and fecal coliform concentrations in waters are frequently employed as an indicator of pathogenic potential. Appropriate Federal and/or state coliform standards must be complied with in order that waterbody classification and allowed usage can be determined. Coliforms are derived from a variety of sources, but generally the most important source with respect to reservoir planning considerations is sewage waste discharge.

As coliform bacteria enter streams along with sanitary wastes, their concentrations initially increase downstream from their source(s) due to population growth. Bacterial density becomes greatest a certain distance downstream, and further downstream bacterial die-off exceeds population growth, leading to a decline in coliform concentration. Die-off patterns are sufficiently systematic that several mathematical formulations are representative (Frost and Streeter, 1924, and Phelps, 1944), but are influenced extensively by a variety of environmental factors. Coliform growth rates are dependent on temperature and seasonal temperature regimes. The amount of rainfall and consequent surface runoff from the watershed, as well as the nature of the surface soils and vegetation, have a direct effect on coliform concentrations in recipient streams.

Stream pH values substantially different from neutrality (either acid or alkaline) can inhibit coliform growth. Die-off rates are typically greater in highly productive systems characterized by appreciable formation of organic material (Kittrel and Furfari, 1963).

The increased retention time of streams brought about by impoundment usually compresses the die-off curve, such that appreciable reduction in coliform standing crops occur in relatively small areas. The key variables to consider in evaluating the potential significance of coliform bacteria in a proposed reservoir are

- (1) What is the nature of coliform die-off in the reach of the stream to be impounded? (Historic coliform data are required and relationships between stream discharge, season, temperature, and BOD determined.)
- (2) What are the projected increases in sewage loading in upstream tributaries in relation to time and distance from the reservoir pool?
- (3) Is anticipated thermal stratification in the reservoir such that surface density currents will occur during the summer? (This will serve to increase the area in which a given magnitude of coliform die-off occurs.)
- (4) Is the anticipated pH of the reservoir substantially different than the neutral (< 6.3 or > 8.3)? (Coliform die-off will be rapid and virtually complete under these conditions.)
- (5) What are present and projected patterns of BOD loading into the impoundment reach of the stream? (If organic loading rates are high, larger incoming populations of coliforms will generally occur, but will die off rapidly under periods of lengthened retention time.)
- (6) What is the intended use of the reservoir? (High concentrations of coliforms in the reservoir or portions of the reservoir will interfere with its direct use as a water supply and, if severe, could restrict some recreational activities such as swimming.)

Homesite/campsite development along the waterfront could act in concert with tributary coliform influx in increasing coliform concentrations in localized areas of the reservoir.)

- (7) What is the nature of the monitoring program designed to keep check on coliform levels in the reservoir? (A comprehensive monitoring program should include provision for regular determination of total coliform, fecal coliform, and fecal streptococci concentrations at appropriate sampling stations within the reservoir.)

A variety of technical literature can be consulted for further information regarding coliform growth and die-off patterns, and how they are influenced by different types of environmental conditions. Kittrell and Kurfari (1963) discuss coliform bacteria growth and die-off in streams. Vanderhoof (1965) and Houghton (1966) provide information on the effect of surface water impoundment on coliform die-off patterns. APHA (1971) presents various methods and their relative advantages and disadvantages for measuring total coliform, fecal coliform, and fecal streptococci concentrations.

Fisheries

When a reservoir is created, the aquatic habitat of the impounded stream changes in so many ways that most fish species which inhabited the former stream do not remain in the reservoir. This is particularly true of game fish species. Generally, the game fish fauna of reservoirs is derived from immigration from other lakes in the watershed of the reservoir and/or by initial or continual stocking from other regions.

Reservoirs are usually classified as "cold water" or "warm water" with respect to potential fishery establishment. Cold water reservoirs are those in which water temperatures are suitable for establishment and maintenance of salmonid populations. This generally requires that temperatures in at least some portions of the reservoir remain below 60-65 F during the summer months. This condition is usually characteristic of deeper reservoirs

in mountainous regions. Warm water reservoirs constitute the remainder, and the fish fauna is comprised of species tolerant of warmer temperatures. The majority of reservoirs in the United States are of the warm water variety. Stroud (1966) estimates that warm water species predominate in about 85 percent of public impoundments. Large reservoirs which undergo regular and appreciable thermal stratification can contain both warm water and cold water species which are vertically segregated during stratified periods.

Fishery development in both cold water and warm water reservoirs tends to follow the same general pattern. Rapid population growth typically occurs during a reservoir's initial fertility subsequent to impoundment. However, game fish are frequently outcompeted by rough fish during initial reservoir development periods. Game fish populations are also subject to other types of stress characteristic of many reservoirs. In the event of appreciable sedimentation rates and/or drawdown, spawning areas may be destroyed. Hypolimnetic oxygen deficiency may be so extensive in eutrophic reservoirs that most or all fish species are confined to the epilimnion during stratified periods. Under these types of conditions a cold water reservoir would be suitable only for warm water species.

In addition to affecting the fish fauna in the impoundment itself, creation of a reservoir can have marked effects on downstream and migratory fisheries, particularly anadromous species. Suitable ladders, locks, artificial transport, or smolt rearing programs may be necessary in these instances for migratory population maintenance.

The effects of reservoir discharges on downstream fisheries are extremely variable depending on season, type of downstream fishery, water temperature, dissolved gases, and method of discharge (e.g., location of discharge ports, spillways, and nature of discharge flow regimen - see Spence and Hynes, 1971, and Frey, 1963).

In addition, downstream effects may not be confined to locations immediately downstream of a reservoir. In cases where the downstream community is dependent on influx of detrital material for a food source, surface water impoundment will markedly reduce fertility and fishery potential. This is a particularly important factor in many types of highly

productive coastal plain estuaries and lagoons (Copeland, 1966; Cooper and Copeland, 1973).

In evaluating the ramifications of reservoir creation to upstream, reservoir pool, and downstream fishery potential, a variety of factors should be considered. These include

- (1) What is the nature of the thermal regime of the reservoir pool? (This will be an important determinant in terms of the types of fish species which the reservoir pool can support.)
- (2) What is the anticipated trophic status of the reservoir? (More fertile, eutrophic lakes will tend to support larger standing crops of fish, but populations of which are comprised of smaller individuals. Hypolimnetic oxygen deficiencies associated with summertime conditions in many eutrophic reservoirs will tend to limit the fishery of the reservoir to a warm water variety.)
- (3) Do migratory species presently utilize upstream (from the dam face) portions of the watershed? (If so, construction of the dam will require incorporation of applicable mitigative measures into the reservoir plan. These may include fish ladders, locks, artificial transport, and/or artificial rearing programs.)
- (4) Will natural colonization of the reservoir be the only means by which game fish are introduced or will artificial stocking also be employed? (Game fish propagation will usually require some degree of artificial stocking, particularly in the early years of the reservoir's existence. Continual stocking may be required if sedimentation prevents spawning success or if angling pressure is heavy.)
- (5) How does discharge water quality relate to near downstream fishery requirements? (Downstream flow rates, discharges, temperatures, and dissolved gas concentrations may all be

deleterious to fish populations. Frey (1963) and Gordon and Hall (1971) should be consulted for specific technical information on this subject.)

- (6) How does the quantitative discharge regimen relate to downstream fishery requirements? (Alteration of the discharge regimen can affect flow rates, stream depth, flooding, and sedimentation patterns. Spawning areas, feeding areas, and food sources can be adversely affected. Pfitzer (1954) and Fraser (1972) should be consulted for additional technical information on this subject.)
- (7) To what extent is the downstream community(s) dependent upon impact of allochthonous detritus for a food source? (If the downstream community in question is heterotrophic ($P/R < 1$), reduction in import of particulate organic materials due to sedimentation will cause a shift to autotrophy and at least an initial decrease in overall productivity.)

A variety of technical literature can be consulted for additional information on the effects of reservoirs on fisheries, both in the impoundments and downstream. Frey (1963), Gordon and Hall (1971), and Varley et al (1971) discuss numerous examples of fisheries development in various impoundments. Frasure (1972), Alabaster (1970), Brett (1957), and Gordon (1965) discuss the effects of impoundments on downstream fisheries due to discharge regimen alterations.

MEASUREMENT CONSIDERATIONS

Ecological impacts entail a reference point from which change can be measured. In order that a reference point be established, data must be collected from the projected impact area. To facilitate evaluation of the various methodologies that may be represented in impact statements, a variety of measurement considerations are discussed, when applicable, as to (1) type of data input, (2) input data needed, (3) assumptions of the technique, and

(4) conditions under which a given technique would or would not be an appropriate methodology.

Terrestrial Ecology Measurement Considerations

Census Data -

A census is a complete or sample count of animals over a specified area at a specific point in time. From these data estimates are made on the total population being manipulated. The methods employed in collecting the data and the form of the calculating formulae will depend on the species, the season of the year, the habitat, the purpose of the study, and on any other feature of the problem that might conceivably influence the observations and the validity of the method. It is assumed here that the worker is familiar with the ecology of the species and with the relevant behavioral patterns and environmental features.

In general, the goal of population estimation should be twofold: (1) to obtain the best possible estimates commensurate with the objectives of the study and the time, resources, and personnel available, and (2) make the estimation within determined limits of accuracy.

Auditory Index -

This technique uses the breeding, feeding, or nesting calls of animals (particularly birds) to determine presence. The investigator must be competent in recognizing species by the sound produced.

Auditory activity is influenced by (1) time of day, (2) weather conditions, and (3) season; thus, a specialist should design the sampling program. When properly used, this methodology is excellent for estimating occurrence and population densities.

Aerial Counts -

Aerial counts are used to estimate large mammal populations for occurrence, size, and distribution. The observer is limited by (1) type

of aircraft available, (2) season and time of count, (3) altitude, (4) observer efficiency, and (5) pilot efficiency. A complete or random search design may be used depending upon the species being counted and the degree of accuracy needed. As individuals are sighted, a mark corresponding to location is placed on a map. In this manner, distribution, occurrence, and numbers of organisms are recorded. This technique has one major disadvantage in that estimates of population densities are consistently low.

Roadside Counts -

Roadside counts (can be called horseback, foot, or spotlight counts depending upon mode of transportation and species counted) of organisms are made by traveling a given distance with designated sampling areas occurring along the way. For example, a count would be made at 1/2-mile intervals for a total distance of 20 miles. Output is expressed as a census index.

$$\text{Census index} = \frac{N}{M}$$

where M = number of miles traveled

N = number of organisms seen.

Factors affecting this technique are

- (1) Abundance
- (2) Activity as affected by time of day, food availability, weather, and season
- (3) Sex of animal or bird
- (4) Condition of roadside cover.

This technique is valid when the areas traversed are representative of the projected impact region.

Drive Counts -

Driving consists of moving the desired organisms past an observer. Techniques are variable depending upon the size of the area and number of personnel involved (aircraft have been used). The minimum requirement is

that two observer teams be present. The drive continues until the driver reaches the observers. Observers count or photograph organisms as they pass.

This technique is limited in that only relative numbers are acquired. Also, species being driven must be amenable to being pushed. It works well in limited areas for large game but is useless for small game or large areas.

Temporal Census -

The temporal census is analogous to the drive method. Here, the spatial dimension is a point and the count is made of all animals passing the point during some interval of time. Count is recorded by visual observation or photograph.

This technique is good for migrating animals that use a definite route.

Pellet Group Count -

Pellet counting entails selecting an adequate number of randomly selected plots in which the feces of the organism being studied is counted. These data are used mostly to determine presence or absence but can also be used as an indices of population level or can be calibrated to give an estimate of actual numbers.

Three assumptions are made for this method: (1) assume a specific defecation rate, (2) assume a period (number of days or hours) over which the groups of fecus have been deposited, and (3) assume that the observers can correctly locate and identify the groups relevant to the population and study period.

Application of the method is as follows:

$$(1) \quad + = \left(\frac{1}{na'} \right) \sum y = \frac{1}{a''} \sum y$$

where $+$ = pellet groups per unit area
 n = number of plots

$\sum y$ = sum of groups counted overall in plots
 a'' = area of one plot
 na' = area of entire sample.

$$(2) \frac{+}{\text{Defecation rate}} = Z \left(\text{days utilization per acre (for the study period)} \right).$$

If the population is assumed constant, Z divided by the number of days in the period (Assumption 2) yields the number of organisms per acre.

This technique is best suited for organisms that defecate recognizable feces. It has been used successfully for deer during the winter months in northern areas. Attempts to use the pellet index in the Southeast have been unsuccessful due to problems of differential decomposition and disappearance of pellet groups.

Radiotelemetry -

Radiotelemetry describes the transmission of information from a sensor element to a measuring system by means of a wireless radio link. There are various types and methods being used from a sensor-recorder fixed, to sensor movable with fixed recorder to no connection between sensor and recorder. This technique is limited only by the sophistication of the equipment employed. Factors that should be considered in setting up a radiotelemeter study include the following:

- (1) Reliability - suitability to task as to field conditions or application
- (2) Accuracy - included in design
- (3) Range - required range for effective transmission must be determined regarding terrain
- (4) Duration - a matter of specification and design; proportioned to capacity of the power source and inversely proportional to the power of the transmission
- (5) Wavelength and interface - depending upon legal restriction, interface, and operational considerations.

Telemetry data are excellent for establishing home range, movements, and migratory patterns.

Carrying Capacity -

Carrying capacity is the number of organisms a given area will support. It can be expressed as K, the upper asymptote of the sigmoid growth curve beyond which no major increase in numbers can occur:

$$\frac{dN}{dt} = \frac{rN(R-N)}{K}$$

where dN/dt = the rate of change in the number of organisms per time at a particular instant

r = instantaneous coefficient of population growth; the difference between the instantaneous specific birth rate (b) and the specific instantaneous death rate (d)

$$r = b - d$$

K = carrying capacity (maximum population size).

K is a function of the size and quality of available habitat. It can be estimated by establishing the major limiting factor inherent within the habitat, i.e., habitat size, food availability, nesting or breeding sites, predation, etc.

Carrying capacity is commonly used in wildlife management and agricultural systems which have the data available for calculations. It can be used to characterize a single species or a community depending upon the complexity desired and the data available.

Physiognomic Methods -

Physiognomic methods are used to present pictorial or graphic descriptions of the vegetation under study (physiognomy is defined as the outward appearance of a community). Species need not be identified when using this method, as structure and form rather than names are used to describe the vegetation (Figure 5). These symbols are then arranged graphically (Figure 6).

This technique allows a presentation of the data to show structure and form. However, it is preceded by a floristic study which identifies species present. It is useful to geographers and other nontaxonomists concerned with the vegetation of the area.

Floristic Methods -

Floristic methods are used when more precise analyses are required. By using these methods, the role of individual species in relation to the "system" can be defined. Also, community groups can be identified. The floristic method considers the following factors:

a. Frequency. Frequency expresses the percentage of sample plots in which a given species occurs.

$$\%F = \frac{X}{N} \times 100$$

F = frequency in percent

X = number of plots species occurred in

N = total number of plots.

It is a statistical idea which is obtained by studying a certain number of sample plots as widely distributed throughout the study area as possible. The frequency index is ordinarily a satisfactory method of expressing occurrence within a community. The major limitation is that enough sample plots must be sampled to give an accurate expression of frequency.

b. Density. Density is the average number of individuals per sampled area. A rough rule of thumb for selecting appropriate plot size is

1. LIFE FORM

- W  erect woody plants
 L  climbing or decumbent woody plants
 E  epiphytes and crusts
 H  herbs
 M  bryoids

2. STRATIFICATION

- 1 more than 25 meters
 2 10 - 25 meters
 3 8 - 10 meters
 4 2 - 8 meters
 5 0.5 - 2 meters
 6 0.1 - 0.5 meters
 7 0.0 - 0.1 meters

3. COVERAGE

- b barren or very sparse
 i interrupted, discontinuous
 p in patches, tufts, clumps
 c continuous

4. FUNCTION

- d  deciduous or ephemeral
 s  semideciduous
 o  evergreen
 i  evergreen-succulent or evergreen-leafless

5. LEAF SHAPE AND SIZE

- o leafless
 n  needle, spine, scale, or subulate
 g  graminoid
 s  medium or small
 h  broad
 v  compound
 q  thalloid

6. LEAF TEXTURE

- o leafless
 f  filmy
 z  membranous
 x  sclerophyll
 k  succulent or fungoid

FIGURE 5. THE SIX CATEGORIES OF CRITERIA TO BE APPLIED TO A STRUCTURAL DESCRIPTION OF VEGETATION TYPES (Phillips, 1959)

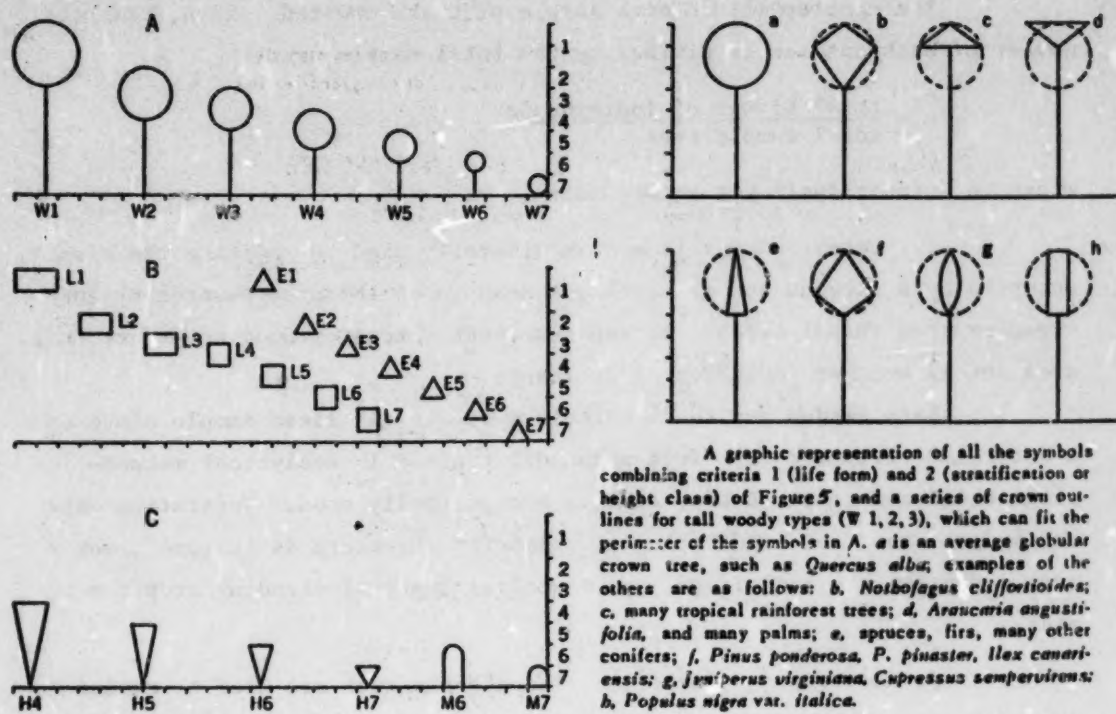


FIGURE 6. SYMBOLS FOR STRUCTURAL DESCRIPTIONS OF VEGETATIVE TYPE (Phillips, 1959)

- (1) Low vegetation, 1 sq. meter
- (2) Medium vegetation, 4 sq. meters
- (3) Trees, 10 sq. meters.

As many sample plots as needed to adequately cover the study area should be sampled.

The species within each sample plot are counted. Then, the total number of each species is divided by the total sample area.

$$d = \frac{\text{total number of individuals}}{\text{total sample area}}$$

where d = individuals per square meter.

c. Cover. Cover is a term generally used to indicate the area occupied by a species and is usually a measure of the area covered by the crown or stem (basal area). It can represent percent ground cover per unit area and is another indicator of dominance.

Data needed for these calculations are (1) fixed sample plots of a determined size and (2) field personnel trained in analytical methodologies and taxonomy. Data output is exceptionally good. Vegetation maps can be prepared, some indication of community structure is achieved, dominant organisms are identified, and a good estimate of standing crop can be made.

d. Succession (Forests). These techniques are used to evaluate forest types. The relative numbers of species (frequency) and age of species (calculated from increment cores taken from trees) are used to establish a time frame for species introduction into the sample area. The data are used to establish the age of and type of community.

Usually, samples are taken along a transect which traverses several environmental gradients to furnish a holistic view of the project area. Then, using the available literature and professional judgment, successional series are established in time and space.

e. Site Index. Site index is defined as the height reached by a species stand at a selected age. It involves measuring the height and age of representative trees within a given area. The index suggests the

"growth potential" of the site, i.e., the culmination of the abiotic factors influencing growth. It is used to develop productivity estimates (logs per unit time).

Site index is arbitrary at best but does allow a relatively quick evaluation of the potential for a site to produce timber.

f. Productivity (Net).

Harvest method - In situations where a specific species is concerned or in plant systems where herbivore consumption is negligible, harvest data can be used as a measure of net productivity.

To calculate, biomass per unit area is collected, dried, weighed and expressed as dry weight per unit area. This method is used for agricultural crops, natural grasses and vegetation, and for forest trees being cut for commercial consumption.

The data are limited in that only net productivity is measured. If samples are not taken periodically throughout the growing season, some plant species may not be included due to a short life cycle. Also, herbivore consumption may be occurring which could (if the amount consumed is large) reduce the accuracy of the data.

Basic method for estimating net plant productivity:

B_1	= Biomass plant community at time t
B_2	= Biomass same community $t_2 (= t_1 + \Delta t)$
$\Delta B = B_2 - B_1$	= Biomass change during $t_1 - t_2$
L	= Plant losses by death and shedding during $t_1 - t_2$
G	= Plant losses by consumer organisms as herbivorous animals, parasitic plants, etc, during $t_1 - t_2$
P_n	= Net production by community during $t_1 - t_2$

Measuring (or estimating) ΔB , L & G we calculate P_n

$$P_n = \Delta B + L + G.$$

Carbon Dioxide Methods - This method equates CO_2 uptake to photosynthetic rates, thus producing a measure of productivity. As with the harvest method, productivity can be calculated for a single organism, species, or community.

Two measurement variations are employed: (1) enclosure and (2) aerodynamic. The enclosure method necessitates physically enclosing a tree or community in a CO₂ impermeable container. Air is pumped in through a monitor where CO₂ content is continually measured. The relationship of the CO₂ intake to CO₂ production (light versus dark) is expressed as productivity. The enclosure method is limited by cost, complexity of the enclosure, and plant response to the "artificial" environment.

The aerodynamic method utilizes periodic measurements of the vertical CO₂ gradient occurs in an open forest or vegetation system. The only modification to the environment is a pole or mast which holds the CO₂ census. However, correction coefficients for the mass movement of air and for CO₂ input from the soil determine the accuracy of the technique. It has been used most in crop or grassland situations.

Aquatic Ecology Measurement Considerations

Composition -

The collection and identification of organisms within a project area are necessary in order to establish which organisms are present. Collection may be accomplished by one or more of a variety of techniques, some of which are more applicable in some situations than others. Identification of organisms collected may be accomplished by the use of appropriate taxonomic keys. Appropriate reference materials for sampling and identification methodologies include Welch (1964), APHA (1973), Pennak (1959), and Edmondson (1965). The information to be derived is of a qualitative instead of quantitative nature, and is used to generate species accounts (lists) for a defined area.

Abundance -

Estimates of the relative abundance of different species within a defined area require the use of quantitative techniques, which give information in terms of weight (biomass) or numbers (abundance/density) of

organisms of a specific type per unit area or volume. Many techniques are used in this regard; fundamentally, they all are designed to register, directly or indirectly, the size (aerial or volumetric) of the portion of the environment which is sampled and organisms which are present therein. The efficiency of sampling processes must also be considered. The applicability of specific techniques to the attainment of specific information is a matter of professional judgment, with due consideration given to accuracy, assumptions involved, and sampling intensity which is required. The plethora of techniques (or modifications thereof) which are used for estimation of abundance precludes an itemization of them, particularly since new ones are developed and brought on-line at a rapid pace. The most complete array of newer techniques used is presented in journals such as Limnology and Oceanography, Transactions of the American Fisheries Society, and other appropriate journals. Many classic (but often outmoded) ones are discussed in Welch (1964) and APHA (1973). A reliable approach designed for assessment of the reliability of the use of a specific technique in a specific situation would include

- (1) Documentation (from the investigator) of the specific technique, and the basis for its selection, including identification of literature pertaining to the specific technique utilized and other techniques which could have been used
- (2) Consultation with expert professional per reliability of information supplied in (1)
- (3) Evaluation (by reviewer) of information gained in (1) and (2).

Temporal Change -

Measurements taken at one instant in time are not necessarily applicable to all time frames. Seasonal sampling should be emphasized, and continuous monitoring programs of key organisms should extend well into the future (post-reservoir construction) if a true assessment of impacts is to be gained.

Short-term temporal factors also play an important role in the significance of composition and relative abundance of species within a community. An organism's relative abundance is not necessarily indicative of its importance in the food web of a community. Productivity of the species' population also must be considered in determining an organism's significance as a material and energy sink and/or source. There are numerous techniques for determining rates-of-change of species' populations and/or food web components (sometimes assemblages of numerous species populations); specific techniques are applicable to specific situations and circumstances. As in the case of techniques for determining standing crops, some latitude of choice is generally available, and final choice is usually a matter of professional judgment. A good deal of background information or a variety of productivity techniques is presented in reviews by Vollenweider (1969) (algae and periphyton), Edmondson and Winberg (1971) (secondary producers), and Ricker (1971) (fish).

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SECTION V
ECONOMIC, SOCIAL, AND AESTHETIC
IMPACTS RESULTING FROM RESERVOIR CONSTRUCTION

As is well known, site specific socioeconomic impact analysis presents many challenges to the writers and reviewers of environmental impact statements. The major problem in assessing socioeconomic impacts is the cost of making reliable projections of site-specific changes. Data inadequacies and the present state of the art of projection models are the two problems which make reliable projections an expensive undertaking. Because of the large number of unknown or difficult-to-predict factors, estimates of future socioeconomic changes resulting from reservoir construction and operations will necessarily be imprecise.

In spite of significant estimation problems, it is possible to make general socioeconomic assessments based on the characteristics of a reservoir project and a knowledge of existing conditions in the project area. This section attempts to provide the impact statement reviewer with a discussion of the general socioeconomic factors that should be included in an impact statement. The section includes a proposed analytical framework for structuring socioeconomic impact assessment as well as brief descriptions of various categories of socioeconomic impacts. No attempt is made to focus on regional considerations or to develop detailed empirical documentation of impacts associated with specific reservoirs. Where literature on given impacts can be identified, references are included with the description of the impact.

A GENERAL FRAMEWORK FOR ANALYZING
SOCIOECONOMIC IMPACTS

Socioeconomic impacts potentially can result from any type of reservoir planning, construction or operation activity. Some impacts may occur simultaneously with a particular activity. Others may require several months or years before their full extent is known. Many times, socioeconomic impacts may be the result of complex regional changes, from which the reservoir effects are difficult to separate analytically.

The general framework described below is an attempt to relate reservoir activities to defined categories of socioeconomic impacts. As in any general representation of a complex problem, arbitrary classifications are unavoidable. The framework should be viewed with this limitation in mind.

Project Activities

Socioeconomic impacts will result directly or indirectly from specific activities under the following general headings:*

- Project Planning
- Project Construction
- Project Operation and Output Characteristics.

The relationship and importance of these project areas to socioeconomic impact assessment is discussed briefly below.

Project Planning -

Socioeconomic impacts can occur even before land for a reservoir is acquired. These types of impacts relate directly to the anticipation of future events caused directly or indirectly by the reservoir project. For example, land values downstream from the proposed project may be bid up in anticipation of flood protection benefits. Other property value changes may occur if nearby residents anticipate recreational development and increased traffic as a result of the reservoir. Anticipation of future reservoir activities may also affect community cohesion. Conflict between individuals supporting environmental preservation and those promoting large scale economic development is a good example.

* Section II of this report provides a detailed discussion of types of project activities.

Project Construction -

Socioeconomic impacts from construction of reservoirs are well known. Among other things, they include displacement of individuals, disruption of transportation routes resulting in change in community cohesion, and change in recreational activities. Construction activities which can lead to these changes include

- Development of access roads and power sources
- Clearing and excavation of the site
- Construction of dam
- Construction and development of associated facilities.

Project Operation and Output Characteristics -

Socioeconomic impacts from operation of reservoirs will depend primarily on the purpose of the project. General types of impacts include change in property values, change in recreational activities, and change in land use patterns. A primary consideration in assessing future changes is the stimulus that the reservoir provides to regional economic development. Operational factors that may cause socioeconomic impacts include

- Reservoir and downstream water level fluctuations related to project function (hydroelectric, irrigation, flood control, water supply and/or recreation)
- Characteristics of newly created reservoir in terms of location and size
- Characteristics and quantity of output of reservoir (power, water supply, navigation, flood control, etc.).

Impact Classification

Project activities will lead both directly and indirectly to socioeconomic impacts. Some types of impacts occur almost immediately whereas others result over time through complex chains of interaction.

For purposes of this report, project activities are seen as causing certain fundamental environmental and economic alterations. These alterations are not end products in themselves but are the basis for broader socioeconomic effects. Alterations are defined as change in physical/chemical, aesthetic, biological, and economic attributes resulting directly from construction and operation of the project. The socioeconomic effects that result from environmental and economic alterations are defined as changes in various measures of human welfare. Traditional measures relate to economic factors such as income, income distribution, property values, and other asset prices. A less precise but equally as important category of measures includes sociological and psychological phenomena such as lifestyle and community cohesion.

Because there is no well defined cut off point for assessment of socioeconomic impacts, a third category is included. This category has various labels depending on one's particular background. It is often called tertiary or ripple effects. These effects result when a reservoir project promotes secondary economic development which in turn creates environmental and economic alterations of its own. These additional alterations may lead to socioeconomic affects similar to those caused by the reservoir. For example, a water supply reservoir may increase the capacity of a local water supply system. In combination with other factors (access to product or other input markets, primarily), the increased water supply may induce a water intensive industry, a brewery for example, to locate in the region. Odor problems that are often associated with breweries may in turn cause downwind residential property values to decline relative to other comparable areas. This impact on property values is termed a tertiary effect. Prediction of tertiary effects can only be done in very general terms, due to the large number of unknown factors that will influence such changes.

Figure 7 presents a list of alteration and effects categories appropriate for assessing socioeconomic impacts. As shown in the figure, project planning, construction, and operation/output characteristics are depicted as causing certain fundamental physical/chemical, biological,

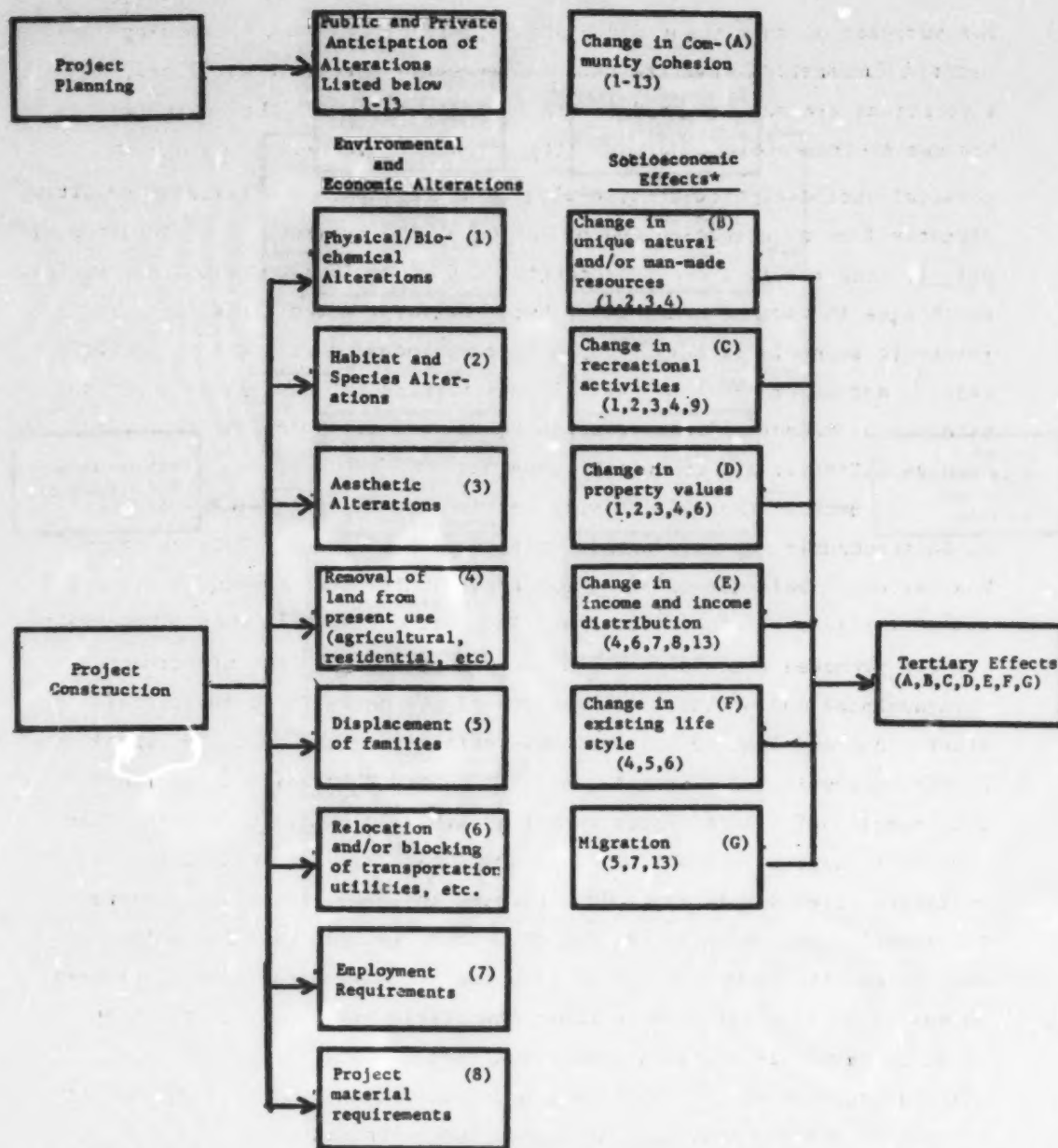


FIGURE 7. SCHEMATIC REPRESENTATION OF SOCIOECONOMIC IMPACTS OF RESERVOIRS

* The alterations that generally cause each listed socioeconomic effect are indicated by the numbers in parentheses.

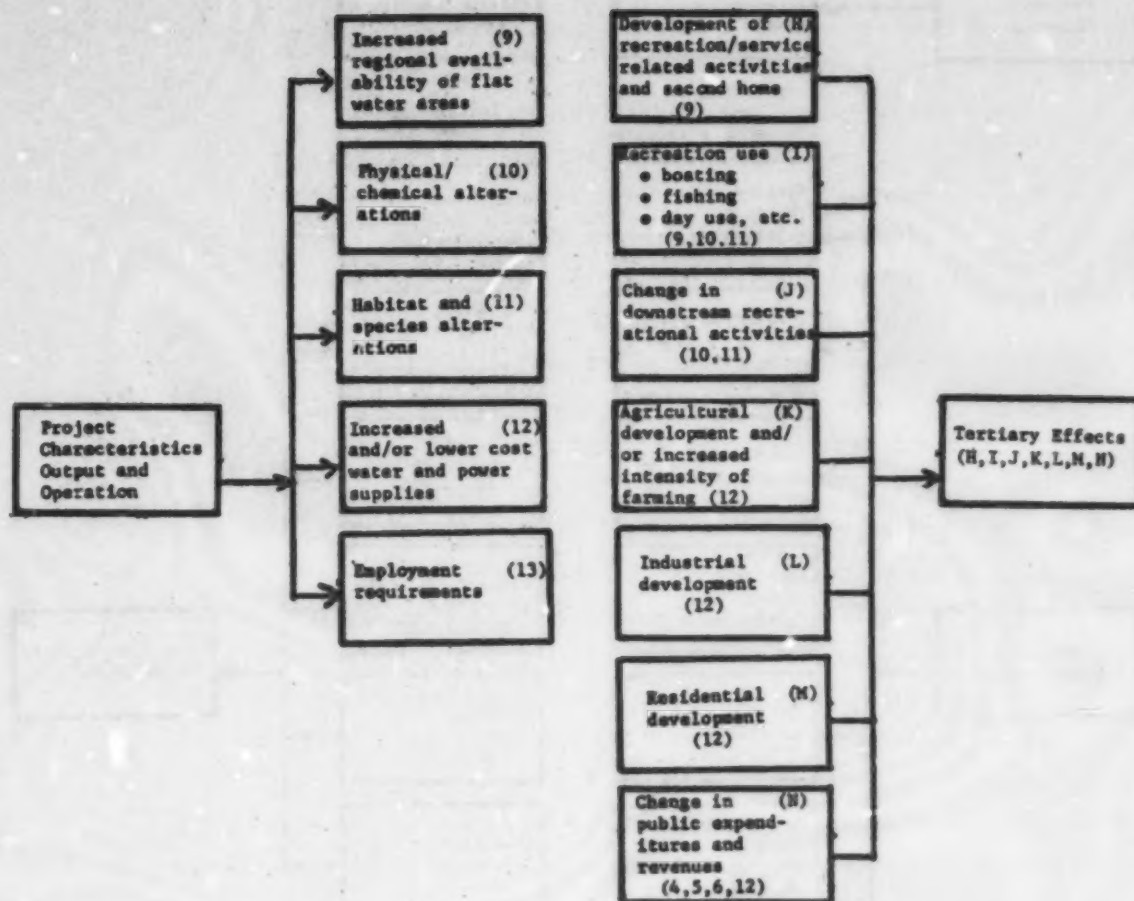


FIGURE 7. (Continued)

economic (and social) alterations. These alterations in turn will affect various socioeconomic variables. The extent to which the socioeconomic variables change will be related to many factors, including:

- Relative magnitude, duration, or frequency of alterations caused by the reservoir (i.e., the percentage change a reservoir causes in the various alteration categories)
- Population density of the immediate region
- Industrial development history and potential of the region (relating primarily to access to transportation systems, to raw materials, to labor and other input markets, and to final product markets)
- Proximity of the immediate region to major population concentrations (relating primarily to recreational use and second home development)
- Characteristics, extent and stability of the ecologic and hydrologic systems altered by the reservoir.

For each socioeconomic effect listed in Figure 7, the alterations that may cause the effect are indicated by the numbers in parentheses. The relation of socioeconomic effects to tertiary effects is not treated explicitly due to the complexity of such relationships. Instead, tertiary effects are treated as one category which is related to the variety of socioeconomic effects. A brief description of each of the alterations and effects identified in Figure 7 is presented below.

SOCIOECONOMIC IMPACT DESCRIPTION

The following general format is used in describing alterations and effects. For alterations, items discussed are definition, description, and determining conditions. For the discussion of socioeconomic effects, the same format is used except that the description relates alterations to effects.

As can be seen from Figure 7, similar types of alterations may result from both construction and operation activities. The socioeconomic effects caused by these alterations are treated under one heading (income, for example) with appropriate reference to the distinction between the project related alterations causing the particular effect. Also, socioeconomic impacts caused by project planning are shown as the result of anticipation of the specified construction and operation alterations.

Environmental and Economic Alterations Planning and Construction Phases

Public and Private Anticipation of Alterations. Most of the political and interest group conflicts associated with a particular reservoir occur in anticipation of reservoir related alterations and effects. The community effect caused by these anticipations will be related to several factors including:

- Number of individuals affected by various anticipated alterations
- Magnitude, character, and duration of anticipated alterations
- Relative political influence of affected individuals (relating primarily to their position in the community, their source of employment, their income levels, their education and background, and their tastes and preferences)
- Proximity of alterations to individuals' property
- Regional and national importance of resources that will be altered by construction and operation of the reservoir.

Literature on the relation of anticipated alterations to socioeconomic effects will be presented below in the discussion of various effects. Explicit consideration of anticipation is treated by Smith (1970).

Physical/Biochemical Alterations (Box No. 1) -

These factors are discussed in detail in Section III. They include fundamental changes in biochemical characteristics of a river system due both to reservoir construction and to changes in the basic flow regimes affecting ground and surface water. Physical/biochemical alterations are included in Figure 7 to show the conceptual relation of environmental alterations to socioeconomic effects.

Habitat and Species Alterations (Box No. 2) -

These factors are discussed in detail in Section IV of the report and are included in this section for the same reason as physical/biochemical alterations. Habitat and species alterations involve direct removal of various classes of habitat (aquatic, marsh, and terrestrial) and the associated destruction of organisms that are unable to migrate from the affected area.

Aesthetic Alterations (Box No. 3) -

These alterations include changes in the natural or man-made visual appearance and alteration in amenity characteristics due to reservoir construction and operation. They include changes in:

- Land (such as surface configurations, land appearance, alignment of streams and reservoir shoreline, and geological surface material)
- Water (in terms of flow, clarity, water level, floating material)
- Biota (such as vegetation, animal life, aquatic life)
- Man-made Structures (such as the dam itself, power transmission lines, and other support facilities)
- Noise
- Odors.

The magnitude of aesthetic alterations will be determined by such factors as the relative uniqueness of aesthetic characteristics that are altered or created, distance that the structures are visible, their height, the materials used in the construction, the extent and magnitude of changes in vegetation along shore lines and the extent of other physical/chemical alterations that may cause odor and plant growth (e.g., algae) problems.

Removal of Land from Present Use (Box No. 4) -

This alteration involves the change in land use status resulting from pre-emption of present uses for the reservoir site and other related facilities. Land use changes resulting from reservoir sites could conceivably be at the expense of a variety of present uses including:

- Agricultural
- Woodland
- Waste land
- Parks or recreational areas.

This alteration is related directly to the extent and size of the given reservoir project (i.e., the number of surface acres inundated as well as land taken adjacent to the reservoir for associated purposes (Higgins, 1967)).

Displacement of Families (Box No. 5) -

Most major reservoirs will involve the displacement of some individuals residing in the areas to be flooded. The extent of this alteration will depend on the population density of the project site as well as the extent of the project. Socio-psychological effects will be discussed in the "effects" part of this section. Some of the factors involved are discussed in various reports and articles (Napier, 1972; Ludtke, et al., 1970; Burdge and Ludtke, 1970).

Relocation of Transportation Systems, Utilities,
Cemeteries, and Other Public and Private
Facilities (Box No. 6) -

Utilization of certain areas for a reservoir site will require either abandonment of existing roads, and/or rerouting of these roads around the high water areas. Similar rerouting may be necessary for power lines, railroads, and possibly for water and sewage facilities. Movement of cemeteries is also often a major problem. The magnitude of this alteration will be directly related to the extent of urbanization in the area.

Employment Requirements (Box No. 7 and 13) -

Reservoir operation and construction activities create demands for various categories of labor and skilled personnel. Relative magnitude of the demand for labor will depend on the scale of the project and the type of facilities (hydroelectric, flood control, etc.) that are being built. General figures on labor requirements are described in various publications ("Labor and Material Requirements...", 1964; Hannon and Bezdek, 1973; Krutilla and Haveman, 1968).

Project Material Requirements (Box No. 8) -

Construction and operation of reservoir projects will also set up demands for specific building materials, aggregates, construction supplies, and other items potentially drawn from the region. The magnitude of this alteration will again be a direct function of the relative scale of the project and the availability of local supplies. The reference provided for the previous category provides general guidance on material requirements.

Environmental and Economic Alterations
Operation Phase

Increased Regional Availability of Flat Water Areas (Box No. 9) -

Construction of a reservoir will increase total acreage of surface waters available in the project region. The size of increase will be directly related to the project purpose, specific modifications in project design aimed at increasing or maintaining minimum pool elevations to maximize surface acreage, and the overall scale of the project. The extent to which increased flat water area will benefit related recreation activities (motor boating, swimming, lake fishing, sailing, etc.) will depend on the number of other lakes and reservoirs in the region and on the regional population density and socioeconomic characteristics. Recreation aspects will be discussed in the "effects" portion of this section.

Physical/Chemical Alterations (Box No. 10) -

Reservoir operations will create a variety of physical/chemical alterations, described in detail in Section III of this report. These alterations are identified in this section of the report in order to show their general relationship to socioeconomic effects.

Habitat and Species Alterations (Box No. 11) -

Reservoir operations (downstream water level fluctuations, for example) may cause alteration in the habitat of certain aquatic species. These types of impacts are discussed in detail in Section IV of the report. They are included in the socioeconomic section in order to indicate the general relationships.

Increased and/or Lower Cost Water and Power Supplies (Box No. 12) -

Depending on project purpose and design, regional availability of water supply and power may be increased as a result of a reservoir project. These output characteristics will in turn create certain locational and development incentives which are discussed in the "effects" portion of this section.

Socioeconomic Effects

A general list of socioeconomic effects that may result from the preceding list of reservoir-related alterations is described below. The reader should refer to Figure 7 for a summary description of the relation of alterations to effects.

Change in Community Cohesion (Box A) -

Reservoir projects will impact various community and regional interest groups differently. Those groups of individuals who may lose real and perceived values because of the project are likely to come into conflict with those that stand to gain from the project. Many of these conflicts and the effects on community cohesion will occur at the planning and design phase of reservoir projects. Since most viable communities undergo change and growth, the significance of interest group conflicts due to a reservoir project will probably diminish with time. More significant will be the changes in lifestyle (Box E), due to displacement of individuals and alterations in land use patterns. General literature on effects of reservoir and water resource projects is presented in Napier (1971); Napier (1972); and Andrews, et al (1972).

Change in Unique Natural and Man-Made Resources (Box B) -

This effect involves degradation, impairment, or loss of unique natural environments and/or man-made resources of unique value. Unique natural environments would be defined as ecologically or geologically rare areas of which the total regional or national supply is strictly limited. Man-made resources could include historical areas, areas of architectural significance, areas of educational interest, or areas with archeological values. Several factors may cause deterioration or loss of unique natural or man-made areas. These factors include physical/chemical alterations (Box No. 1), habitat and species

alterations (Box No. 2), aesthetic alterations (Box No. 3), and removal of land from present uses (Box No. 4). Change in unique and natural man-made areas will, of course, be dependent on their presence in the project site and immediate area.

Loss of unique or natural man-made resources will have many ramifications. It decreases their abundance on a national basis and creates a regional loss if they are an attraction of importance for visitors from other regions. Loss of visitation will create an economic decline associated with this activity and result in displacement of certain activities in the regional economy. Loss of unique natural man-made resources will also create psychological losses for certain members of communities, depending on their preferences and perceptions. Irreversible change in the status of these resources represent a loss not only to regional inhabitants but to the nation and to future generations.

Change in Recreation Activities (Box C) -

This effect involves changes in present activity patterns associated with the reservoir site. (Recreational use of the reservoir and downstream recreational use will be discussed separately below.) Items of major interest include the type and extent of hunting, the type and extent of river fishing, the utilization of the river for canoeing and related free-flowing water activities, and the utilization of the area for other recreational pursuits such as hiking, camping, picnicking, and nature study and observation. Factors causing change in these activities are the same as those for the above effect:

- Physical/biochemical alterations (Box 1)
- Habitat and species alterations (Box 2)
- Aesthetic alterations (Box 3)
- Removal of land from present use (Box 4).

Factors determining the extent of change relate primarily to the scale of the reservoir project and the present (or potential) activities in the site area. Tertiary effects include decline in employment of stream related recreation enterprises.

Change in Property Values (Box D) -

Change in property values involves an increase or decrease in the average values of specific properties over and beyond that which would normally occur without the reservoir. Construction and operation activities can cause change in property values of a temporary or permanent nature for several reasons. These include:

- Aesthetic deterioration due to alterations of the environment around the construction site (Box No. 3)
- Removal of certain parcels of land from present use
- Alteration in the physical or biochemical environment creating odor or other amenity problems
- Creation of development potential due to reservoir operation and output characteristics
- Creation of traffic and congestion associated with recreational use.

Conditions determining the effect on property values are related to two important factors. One is the sensitivity of the present use to alterations in the surrounding environment. Impact on agricultural use will probably be minimal from aesthetic or amenity alterations in the neighborhood of the reservoir. On the other hand, proximity to residential areas (during the construction phase) may have a retarding effect on property values. This effect will primarily be evidenced as a slower rate of increase rather than any noticeable decrease. Proximity to urban areas and potential recreation demand will also play an important role in property value changes.

Tertiary effects from change in property values are hard to trace and all that can be done is to identify potential areas of concern. One of these relates to Box D in terms of change in income. Effects on property values also may have broader effects in terms of changing the character of neighborhoods or altering the development characteristics of a particular area. Literature includes Milliken (1967) and Drucker (1972).

Change in Income and Income Distribution (Box E) -

Change in income involves an increase or decrease in the annual wages, salaries, interest, profit, or rent received by individuals in the region of the reservoir. Several alterations can cause a change in income. These include:

- Removal of land from present use (Box No. 4)
- Disruption of transportation (Box No. 6)
- Project employment requirements (Box No. 7)
- Project material requirements (Box No. 8)
- Developmental stimulus provided by the reservoir outputs.

Construction of the reservoir will alter income by taking certain lands out of production, by creating demands for certain factors of production such as labor or raw materials, and by causing temporary changes in the income earning capacity of the land due to disruption of transportation or other public service systems. The conditions determining the magnitude of these effects will be related to the present use and economic activity in the neighborhood of the reservoir as well as the scale of the project. Development of land surrounding the reservoir and industrial location may also result in new sources of income for the region.

Factors determining the magnitude of changes in income distribution include:

- Employment and skill categories required in construction and operation of the reservoir
- Patterns of land ownership
- Magnitude of development stimulated by presence of the reservoir and ownership of income earning assets which are positively or negatively affected by development
- Methods of financing public services needed as a result of development.

For example, if large numbers of unskilled workers are employed at high wages, one could expect an increase in income in those categories.

If marginal farmers are forced off the land because of the project, decreases in income to these individuals could be expected.

Tertiary effects will depend on the magnitude of the project relative to present activities. In most cases, change in income earning capacity of labor and assets in the region will have a multiplier effect through expenditure of income on consumer goods and services. These expenditures may in turn create demands for further consumer serving businesses which will generate additional sources of regional income. Other income generation factors relate to industrial location and secondary development, as discussed below. More detailed material on the subject is given in U.S. Department of Labor, Bureau of Labor Statistics (1964), Saitta and Bury (1973), Levin (1969), and Andrews (1972).

Change in Existing Life Styles (Box F) -

This effect involves the disruption of existing social patterns, means of livelihood, or particular characteristics associated with work, recreation, and social tradition in a given region. The major alterations which will effect life style include the removal of land from present use (Box No. 4), displacement of families (Box No. 5), and relocation or blocking of transportation and utilities (Box No. 6). Each of these alterations has a potential for causing major shifts and change in existing work and activity patterns. Alteration of the physical and ecological environment also can produce changes in existing life styles. This results because of alterations in the character of the area and because of change in recreational activities that may follow (Box C above). Industrial, recreational, residential, and agricultural development (discussed below) may also cause change in existing life styles. Alteration of life style will be a direct function of the scale of the project as well as the uniqueness of the life style in a given area. Areas with considerable urbanization can be expected to suffer lesser magnitude effects than areas with rural character or deeply ingrained traditions.

Tertiary effects from change of life style are often difficult to separate from pervasive technical, economic, and social trends in

society as a whole. Tertiary effects that can be identified include other socioeconomic effects such as change in recreational activities (Box C), and out migration (Box G). Other tertiary effects might be found in urban areas to which displaced or unemployed people migrate. These effects could include increased welfare payments, unemployment, or other related urban social problems.

Literature on the subject includes those references cited under "displacement of families" as well as Baur (1973), Utah State University (1968), Andrews (1972), and Prebble (1969).

Migration (Box G) -

This effect involves the voluntary or involuntary movement of people over a specified distance. Alterations causing migration include removal of land from present use (Box No. 4), displacement of families (Box No. 3), and employment requirements (Box No. 7). Conditions determining the magnitude of this effect will be related to the population density of the reservoir area, job opportunities in the immediate area as present economic activities are displaced, and the distance to other major areas of employment. Mobility of families based on educational level and training will also be a factor in the degree of migration that occurs.

Tertiary effects relate to other socioeconomic effects such as change in existing life style (Box F) and to increased social problems in urban areas.

References on migration and displacement were presented previously in the discussion of "displacement of families" (Box No. 5).

Development of Recreation/Service Related Activities and Second Homes (Box H) -

Development of a reservoir creates new water areas on which flat water recreation can be pursued. This in turn may stimulate private investment in service and supply related activities. It is also possible

that land adjacent to the reservoir may be developed over time for second homes. Primary characteristics determining the potential for these developments will be the physical dimensions of the reservoir, its surface area, and its general attractiveness. Conditions which will determine the extent of these developments include the proximity to urban areas and to interstate highway systems, income levels in the region, and the availability of alternative areas of similar characteristics.

Tertiary effects and pertinent references are discussed below under recreational use. One specific study on second home development has been conducted by Burby (1971).

Recreational Use (Box I) -

Creation of a reservoir and the provision of associated facilities and services will result in certain recreational use. Recreational use may include boating of various types (power boating, sailing, canoeing), fishing, day use (such as hiking and nature observation), and overnight camping. The extent of recreational use will be determined by the features of the reservoir, population density, per capita income levels in the region, and the availability of other recreational areas. Limitation on use may result if physical/chemical changes create offensive water quality conditions or undesirable ecological changes.

Tertiary effects of recreation development will relate to two important areas. One is the environmental impact these developments and their use cause. The other is the economic implications in terms of income and employment. Development of recreational facilities and private enterprises requires construction and facilities development which generates its own forms of land use change and potential environmental degradation. For example, traffic congestion and boating use on the reservoir have potential environmental impacts. The extent of these impacts and their importance will be determined both by the magnitude of recreation use and facility development (including second

home development). Also the size of the reservoir project and its ability to assimilate both pollutants and large numbers of recreationists will determine the significance of this tertiary effect.

The other aspect of recreation development is the generation of income and employment. Construction and operation facilities will mean employment and income to residents of the region. This may have positive effects on unemployment, welfare payments, and in the long run, on overall education and health levels of the population.

Development of the area for recreational activities will also have a tertiary effect in terms of relation to life style (Box F). Certain lands may go out of one type of land use (agriculture, for example) and be put to more intensive uses such as marinas or boat sales and service facilities. References on the general subject of recreation development and use include Saitta (1973), U.S. Department of Interior (1971), and Milliken and Mew (1969).

Change in Downstream Recreational Activities (Box J) -

Reservoir operation may lead directly or indirectly to change in recreational activity patterns below the reservoir. These may include increased fishing in the tail race and change in the type of fishing and hunting activities conducted in reaches below the reservoir. Alterations which will be significant in causing such changes include habitat and species alterations due to altered habitat (water level fluctuations) and physical/biochemical alterations causing subtle changes in riverine ecology. These alterations and impacts are discussed in Sections III and IV. Conditions determining the magnitude of change in downstream recreational activities will depend on present activities, sensitivity of the environment to subtle biochemical/physical alterations, and the scale of the project relative to the overall minimum, average, and maximum stream flows.

Tertiary effects relate to change in life style (Box F) and indirectly to certain changes in income earning capacity of enterprises which cater to existing recreational activities. References on the subject include Dearing (1968), Dearing and Woolrine (1973), and Bianchi (1969).

Agricultural Development and/or Increased
Intensity of Farming (Box K) -

Depending on project purpose, a reservoir project may lead to agricultural development or more intensive farming on already irrigated lands. Alterations that will create this potential relate primarily to the increased availability of water or lower cost water supplies. Conditions which will permit realization of these potentials include the fertility of the soil, development costs in the area, access of the area to markets, and overall level of demand for agricultural products.

Tertiary effects from agricultural development include both the regional economic stimulus (wages and income) and environmental changes in terms of potential degradation of waterways (from erosion, pesticide, and fertilizer run off) and alteration of local terrestrial ecology due to clearing of vegetation. In the extreme, secondary developments in housing and support facilities for agricultural development could be expected. The conditions determining these tertiary effects will be directly related to the purpose of the reservoir project and the market potential for development. References on the secondary stimulus of agricultural development may be found in various Department of Agricultural experiment station reports and in agricultural economic journals. Bureau of Reclamation publications are another possible source of information. Other references include Rainer and White (1971), Regan and Timmons (1954), Regan and Steel (1957), Hargrove (1971), and Leven (1969).

Industrial Development (Box L) -

Power and water outputs from the reservoir may induce certain industrial locations in offsite areas. Alterations creating this potential will relate directly to increased and/or lower cost water and power supplies (Box No. 12). Conditions determining realization of the potential will relate to the proximity of the reservoir to urban areas, the requirements of industries for water and power supplies, and the proximity of the region to broader regional and national markets.

Tertiary effects again relate to environmental and economic factors. Industrial development has the potential for altering land use through its own location. Corresponding population increases may result from influx of workers with demands for homes, retail services, and public facilities and services. All of these potential developments in turn have environmental consequences and effects associated with them. These involve impacts on several of the alterations areas such as physical/chemical and habitats and species. Alterations also occur through pollution and physical removal of habitat.

References on industrial development stimulus provided by reservoirs include Regan and Steel (1957), Hargrove (1971), and Leven (1969).

Residential Development (Box M) -

Residential development will be intimately related to many of the other socioeconomic effects such as recreational use, industrial or agricultural development, and to alterations involving increased or lower costs water supplies. Conditions determining residential development will relate directly to the economic development potential facilitated by construction and operation of the reservoir.

Tertiary effects will be similar to those discussed above under industrial development and relate to change in land use and environmental side effects through the increased urban runoff, air pollution, and ecological changes.

References include many of those already presented, especially Burby (1971).

Change in Public Expenditures and Revenues (Box N) -

Recreational use, residential and industrial development, and regional population growth may result directly or indirectly from reservoir projects. These developments in turn create demands for public services (roads, schools, water and sewer, police and fire protection, etc.) and

create new sources of revenue (state and local income taxes, state excise taxes, municipal and county property taxes, and user charges). Determining the net effects on public expenditures is an important consideration in analyzing socioeconomic effects including income distribution, community cohesion and regional economic stimulus. References include Saitta (1973), Bates (1970), Drucker (1972), and Smith (1972).

SUMMARY

This section presented a very general framework for identifying the socioeconomic impacts of reservoir projects. In using the framework, the impact statement reviewer should refer to the various footnotes cited for each impact area. These references provide in depth treatment of technical and conceptual aspects of socioeconomic impact evaluation as well as examples of specific case studies. An excellent general reference is "Water Policies for the Future" (National Water Commission, 1973). The reviewer should also keep in mind the limitations of arbitrary classification schemes, including the one presented in this section.

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SECTION VI

REVIEW CRITERIA

Environmental impact statements on reservoir construction activities provide information about how a proposed project will affect the environment. If well done, an impact statement can be an important summary of information vital to the decision-making process. In addition, the impact statement will generally be the principle source of information about a project and its implications available to the public at large. Consequently it is essential that the statement cover all significant factors and provide accurate, useable findings. The difficult function of an EPA reviewer is to determine whether the information contained in the statement is complete and accurate.

One approach, of course, is for the reviewer or decision-maker to duplicate the analysis and develop his or her own environmental statement. This may be the surest way, but it is certainly not efficient in terms of time and resources required to do the job. It essentially requires a doubling of resource requirements for every statement developed.

A second approach is to utilize a set of predetermined criteria against which the completeness and accuracy of a statement can be tested. This approach, while less certain of identifying inadequacies, can provide a reasonably sound evaluation of a statement in a short period of time with a minimum of resources.

The purpose of this section is to provide such criteria for judging impact statement adequacy and completeness. It should be emphasized that the function of these criteria is to assure that the most important questions are asked during the course of a review; not to provide an assessment of overall project acceptability.

Two levels of review criteria are important. One level uses information such as that provided in the Water Quality Impacts and Ecological Impacts sections of this report to ask rather detailed questions about specific aspects of the environment that may be impacted by reservoir construction. This research has not attempted to develop a complete list of such specific criteria for any impact area but does suggest several important considerations, particularly on pages 97 through 129.

It is difficult, however, to assess the completeness and accuracy of an environmental impact statement with respect to specific impact areas without some feel for the degree of confidence that can be placed in more general information regarding the project and its impacts. For this reason, a set of general review criteria are needed, applying to the impact statement as a whole. Such a set is presented in Table 13 and discussed in the following pages.

No strictly objective procedures can be developed that will adequately evaluate all possible impact statements. The use of both general and specific review criteria must be tempered by the judgment of the reviewer--especially in determining when an item may or may not be significant and when the level of accuracy is adequate or inadequate. Unique site characteristics, extenuating circumstances, and gradation of impact will require that the reviewer be the ultimate judge of the adequacy of impact statements.

GENERAL REVIEW CRITERIA

Completeness

Project Description -

The project description should include detailed project maps showing the layout of buildings, dams, and other structural changes, engineering designs and drawings depicting construction details, operating procedures, and equipment to be employed. The visual aspects of the entire project should be presented in architectural drawings.

In addition, the project description should include plans for inspection and monitoring programs and contingency plans for environmental quality control throughout the reservoir construction and operation phases. The flow of materials to and from the project site should also be discussed, including the quantities and sources of raw materials and the sources and shipping routes of these materials if pertinent.

TABLE 13

GENERAL ENVIRONMENTAL IMPACT STATEMENT REVIEW CRITERIA

A. Completeness

1. Project Description. Are the proposed project activities adequately described, through the inclusion of sufficient maps, sketches, construction timetables, etc.?
2. Present Situation. Are present conditions in the project area adequately described in terms of land use, environmental, economic, and social conditions?
3. Project-Caused Impacts. Has an explicit attempt been made to isolate project-generated impacts from other changes in the project area resulting from activities not associated with the proposed project?
4. Timing and Duration. Does the statement indicate precisely when specific project activities will take place and for how long a time they will be continued?
5. NEPA Points. Does the statement include all the required contents specified in NEPA and in subsequent CEQ guidelines?
6. Data Sources. Are the sources of all information used to predict and evaluate environmental impacts adequately documented?
7. Tool Identification. Are the specific analytical tools, models, or methodologies employed to predict impacts or evaluate impact significance identified?
8. Analyst Identification. Are those individuals who conducted the actual impact analysis identified by name and background?
9. Uncertainty and Risk. Does the statement indicate the analysts' level of confidence in the predicted impact magnitudes? Does the statement discuss (or explicitly assert the nonexistence of) any high risk-low probability impacts?
10. Affected Parties. Does the statement specifically identify those segments of the public who will be directly impacted by the project?
11. Key Issues. Does the statement include a summary, highlighting the most important conclusions of the analysis that may be important in the making of a public decision?

B. Accuracy

1. Geographic Scope. Are the geographical boundaries used for analysis broad enough to include all identifiable impacts or can the reviewer identify potentially important impacts in areas outside those boundaries?
2. Time Scope. Has the entire time frame of the project been analyzed for potential impacts, including construction, operation, and ultimate disposal of the site?
3. Methods and Procedures Accuracy. Does the reviewer have any basis for asserting that the analytical procedures used in identifying and measuring impacts are inadequate or inappropriate?
4. Data Reliability. Does the reviewer have any basis for questioning the accuracy, reliability, or appropriateness of data cited to support conclusions?

TABLE 13. (Continued)

5. Analyst Qualifications. Assuming the responsible impact analysts are identified, are their areas of expertise and backgrounds appropriate to impacts in question?
6. Magnitude vs. Importance. Does the impact statement make a clear distinction between the predicted size of impacts (magnitude) and the significance of these impacts (importance)?
7. Evaluation Documentation. Does the statement identify the rationale, criteria, or other bases supporting any subjective judgments of impact significance?

Present Situation -

The description of the existing situation should include maps and tabulations of current land use in the entire region that may be affected by the project. Also, current types, levels, and trends in economic and social activities in the region should be detailed and quantified (e.g., population, housing, number of employees, and output of major firms; number of annual user days at each recreation site, etc.).

The ecological characteristics of the area should also be detailed and their relationships to areas and activities outside the direct influence of the project should be clearly described. Current environmental conditions should be quantified, and also described in terms of trends. Air and water quality, noise levels, traffic patterns, levels of existing resources and services (water supply, sewage treatment and disposal, power) must all be identified and described. All the foregoing data should be consistent with current official data available to the reviewer.

Project-Caused Impacts -

Since changes in the economic, social, and environmental characteristics of the region will undoubtedly occur with or without the project, it is important that those impacts specifically attributable to project activities be identified as separate from changes expected to be produced by other causes.

Timing and Duration -

The temporal pattern of environmental impacts is an important issue often overlooked. Reservoir construction projects may have markedly different impacts, particularly in the areas of water quality and ecology, during the construction phase, during early operational phases, and as the project nears the end of its useful life. The potential for such significantly different impacts over time should be addressed in the impact

statement as should the duration of such impacts; that is, does an impact occur once for a brief period, once for an extended or permanent period, or repeatedly in a cyclic manner?

NEPA Points -

A complete environmental impact statement must, as a minimum, address the specific points of statement content set forth in the National Environmental Policy Act of 1969 and in subsequent guidelines put forth by the Council on Environmental Quality (CEQ). The most recent CEQ guidelines, dated August 1, 1973, identify eight specific content areas required:

- Description of the proposed action
- Relationship of the proposed action to land use plans, policies, and controls for the affected area
- Probable impact of the proposed actions on the environment
- Alternatives to the proposed action
- Any probable adverse environmental impacts which cannot be avoided
- Relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity
- Any irreversible and irretrievable commitments of resources
- An indication of what other interests and considerations of Federal policy are thought to offset the adverse environmental effects identified.

Data Sources -

Data used in predicting and evaluating impacts should be adequately documented so that decision makers, members of the public, or the reviewer can consult original sources for further information or verification. Such specific citation is a required first step in the analysis of data accuracy and reliability.

Tool Identification -

As is illustrated in the Water Quality Impacts and Ecological Impacts sections of this report, a variety of techniques may exist for predicting impacts in any given area. Since each technique is appropriate in some circumstances but not in others identification of the specific techniques used is a prerequisite to the reviewers' analysis of tool appropriateness.

Analyst Identification -

NEPA requires that impact analyses be conducted by an interdisciplinary team. An environmental impact statement should identify this team both by name and by area of expertise.

Uncertainty and Risk -

In all project situations, some impacts are virtually certain to occur while others are very difficult to predict with confidence, being highly dependent on future events. A complete environmental impact statement should indicate the level of confidence the analysts have in impact prediction. This information is particularly important when impacts are quantified. An adequate impact statement should also identify any impacts of low probability but high damage or loss potential. If no such high risk impacts can be foreseen the statement should so state.

Affected Parties -

Since an impact statement is intended to communicate information to the public, wherever identified impacts will impinge upon a specific segment of that public, defined in either geographic or socio-economic terms, the group should be specifically identified. For example, reservoir construction frequently replaces a cold, flowing water fishery with a warm, still water one. Typically, a distinctly different group of recreationists will utilize these two fisheries.

Key Issues -

An impact statement must be comprehensive and discuss all identifiable impacts, but it must also provide some guidance for public decision making. The key conclusions of the impact analysis, including expected major positive impacts, major negative impacts, areas of little or no impact, and levels of certainty should be given special prominence to guide public discussion.

ACCURACY

Geographic Scope -

Important environmental impacts may frequently occur outside the immediate project area and should be identified in the impact statement. Such impacts are particularly important in reservoir projects where major downstream alterations can be expected. Any geographical boundaries chosen for analysis are artificial and in some sense arbitrary, but the boundaries utilized in any impact statement analysis should be clearly specified and the reviewer should be unable to cite any specific project-related impacts identifiable outside the region of analysis.

Time Scope -

Impacts should be analyzed over the entire life span of a project, including construction, operation, and final disposition of the reservoir site. An adequate impact statement should address all of these periods and assign specific dates to them as well. A statement is inadequate if the reviewer can identify an impact directly generated by the project occurring outside the time scope of analysis.

Methods and Procedures Adequacy -

The reviewer must evaluate the adequacy of analytical techniques used in the impacts analysis. Impact statement accuracy can be judged

satisfactory only if the reviewer concludes that the techniques used to identify, predict, and evaluate impacts are appropriate to the circumstances and warrant the conclusions made. Data such as that provided on water quality and ecological impact prediction methodologies presented in other sections of this research will be required by the reviewer in making this evaluation.

Data Reliability -

Regardless of the techniques employed, impact assessments may be invalid if the data used is incomplete, unreliable, out of date, or statistically inadequate. Though it may be difficult for the reviewer to make a determination on data reliability, an attempt should be made to address the point.

Analyst Qualifications -

The findings of an environmental impact statement may be inaccurate if they are produced by individuals unqualified to speak with authority on the area in question. The reviewer should examine an impact statement to determine whether the appropriate breadth and depth of disciplinary skills is represented on the project team to justify the assertions made in a statement.

Magnitude vs. Importance -

Impact significance is not necessarily directly related to impact size. Unique site and regional characteristics are major determinants of impact significance not necessarily automatically reflected in objective measures of impact magnitude. Professional judgments and personal values may also result in differing significance interpretations being placed upon impacts of the same magnitude. An impact statement, therefore, should explicitly differentiate between purely objective quantitative measurements of impacts and evaluative statements of impact significance.

Evaluation Documentation -

The environmental impacts identified in impact statements are never all of equal importance. Some evaluation, including subjective judgments, is always required to identify those impacts which are key. The accuracy of impact statements should be reviewed to discover the basis of such evaluation. This review may indicate a consistent and obvious bias or it may fail to indicate any consistent basis for evaluation. An adequate impact statement in contrast, explicitly states the viewpoints or criteria upon which subjective evaluations are based.

SECTION VII

A REVIEW OF ENVIRONMENTAL IMPACT

ASSESSMENT METHODOLOGIES

Environmental impact analysis, as required by the National Environmental Policy Act of 1969 (NEPA), is more art than science. There are no universally applicable procedures for conducting an adequate analysis. There are, however, a wide variety of assessment tools and even comprehensive methodologies that may make preparation of an environmental statement a less formidable and more meaningful task. This section describes and critically analyzes 17 of these tools and offers suggestions on choosing those tools or methodologies which may apply to the specifics of a particular environmental assessment situation.

In only a few cases are the tools discussed full-blown methodologies developed specifically for impact statement preparation. More commonly, they are more limited ideas borrowed from other fields with potential application to NEPA environmental assessments. None of these tools has been widely applied as yet in actual impact statements; indeed, many have never been so used.

This discussion is not intended as a step-by-step "cookbook" to the use of these tools; very rarely would any of them be directly applicable to any specific situation without modification. Instead, key ideas that one may find useful are discussed and the tools are described in sufficient detail to help the reader identify those which he or she might wish to examine more fully.

CHOOSING A METHODOLOGY

There is no single "best" methodology for environmental impact assessment. Characteristics of a methodology such as types of impacts or projects covered and resources required may be virtues in one instance, vices in another. Only the user can determine which tools may best fit a specific task. In selecting the most appropriate tools the following key considerations may be useful:

1. Use. Is the analysis primarily a decision or an information document? (A decision document is vital to determining the best course of action, an information document functions primarily to reveal the implications of a single, clearly best choice.) A decision document analysis will generally require greater emphasis on the identification of key issues, on quantification, and on direct comparison of alternatives. An information document requires a more comprehensive analysis concentrating on interpreting the significance of a broader spectrum of possible impacts.

2. Alternatives. Are alternatives fundamentally or incrementally different? If differences are fundamental, such as preventing flood damage by levee construction as opposed to flood plain zoning, for example, then impact significance can better be measured against some absolute standard than by direct comparison of alternatives since impacts will differ in kind as well as size. Fundamentally and incrementally different alternative sets require different levels of analysis to discriminate between alternatives, in that incrementally different alternatives require a greater degree of quantification.

3. Public Involvement. Does the anticipated role of the public in the analysis involve substantive preparation, token review, or vital review? The first two roles allow use of more complex techniques such as computer or statistical analysis that might be difficult to explain to a previously uninvolved but highly concerned public. A substantive preparation role will also allow a greater degree of quantification or weighting of impact significance through the direct incorporation of public values.

4. Resources. How much time, skill, money, data, and computer facilities are available? Generally, more quantitative analyses require more of everything.

5. Familiarity. How familiar is the analyst with both the type of action contemplated and the physical site? Greater familiarity will improve the validity of a more subjective analysis of impact significance.

6. Issue Significance. How big is the issue in terms of controversy and scope? All other things being equal, the bigger the issue the greater the need for explicitness, quantification, and identification of key issues and the less appropriate become arbitrary significance weights or specific formulas for trading off one type of impact (e.g., environmental) against another type (e.g., economic).

7. Administrative Constraints. Are choices limited by agency procedural or format requirements? Specific agency policy or guidelines may rule out some tools by specifying the range of impacts to be addressed, the need for analysing trade-offs, or the time frame of analysis.

CATEGORIZING METHODOLOGIES

The various methodologies examined can be divided into five types, based on the way impacts are identified:

- (1) Ad hoc: These methodologies provide minimal guidance to impact assessment beyond suggesting broad areas of possible impacts (e.g., impacts on flora and fauna, impacts on lakes, forests, etc), rather than defining specific parameters to be investigated.
- (2) Overlays: These methodologies rely on a set of maps of environmental characteristics (physical, social, ecological, aesthetic) for a project area. These maps are overlaid to produce a composite characterization of the regional environment. Impacts are identified by noting the impacted environmental characteristics lying within the project boundaries.

- (3) Checklists: These methodologies present a specific list of environmental parameters to be investigated for possible impacts but do not require the establishment of direct cause-effect links to project activities. They may or may not include guidelines on how parameter data are to be measured and interpreted
- (4) Matrices: These methodologies incorporate a list of project activities in addition to a checklist of potentially impacted environmental characteristics. These two lists are related in a matrix which identifies cause-effect relationships between specific activities and impacts. Matrix methodologies may specify which actions impact which environmental characteristics or may simply list the range of possible actions and characteristics in an open matrix to be completed by the analyst.
- (5) Networks: These methodologies work from a list of project activities to establish cause-condition-effect networks. They are an attempt to recognize that a series of impacts may be triggered by a project action. These approaches generally define a set of possible networks and allow the user to identify impacts by selecting and tracing out the appropriate project actions.

REVIEW CRITERIA

To serve the purposes of the National Environmental Policy Act of 1969 (NEPA), an environmental impact assessment must effectively deal with four key problems:

- Impact identification
- Impact measurement
- Impact interpretation
- Impact communication to information users.

Based upon experience with impact assessments to date, a set of 20 criteria for methodology evaluation can be defined covering these four key problems. These are:

• Impact Identification

1. Comprehensiveness. An impact methodology should address a full range of impacts including: ecological, physical-chemical pollution, social-cultural, aesthetic, resource supplies, induced growth, induced population or wealth redistribution, and induced energy or land use patterns.
2. Specificity. A methodology should identify specific parameters (subcategories of impact types) to be examined.
3. Isolate Project Impacts. A methodology should require and suggest methods for identifying project impacts as distinct from future environmental changes produced by other causes.
4. Timing and Duration. A methodology should require and suggest methods for identifying the timing (construction phase vs. short-term operation vs. long-term operation phase) and the duration of impacts.
5. Data Sources. A methodology should require identification of the sources of data used to identify impacts. (Data sources should also be listed for impact measurement and interpretation.)

• Impact Measurement

6. Explicit Indicators. A methodology should suggest specific measurable indicators to be used to quantify impacts on parameters.
7. Magnitude. A methodology should require and provide for the measurement of impact magnitude as distinct from impact significance.
8. Objectivity. A methodology should emphasize objective rather than subjective impact measurements.

● Impact Interpretation

9. Significance. A methodology should require explicit assessment of the significance of measured impacts on a local, regional, and national scale.
10. Explicit Criteria. A methodology should require that the criteria and assumptions employed to determine impact significance be stated.
11. Uncertainty. A methodology should require an assessment of the uncertainty or degree of confidence in impact projections made.
12. Risk. A methodology should require identification of any impacts of low probability but high potential damage or loss.
13. Alternatives Comparison. A methodology should provide a specific method for the comparison of alternatives, including the no-project alternative.
14. Aggregation. A methodology may provide a mechanism for aggregating impacts into a net total or composite estimate. If aggregation is provided for, specific weighting criteria or processes to be used should be identified. The appropriate degree of aggregation is a hotly debated issue on which no judgment has been made in this review.
15. Public Involvement. A methodology should require and suggest a mechanism for public involvement in the interpretation of impact significance.

● Impact Communication

16. Affected Parties. A methodology should require and suggest a mechanism for linking impacts to the specific affected geographical or social groups.
17. Setting Description. A methodology should require a description of the project setting to aid statement users in developing an adequate overall perspective.

18. Summary Format. A methodology should provide a format for presenting in summary form, the results of the analysis.
19. Key Issues. A methodology should provide a format for highlighting key issues and impacts identified in the analysis.
20. NEPA Compliance. A methodology should provide guidelines for summarizing results in terms of the specific points required by NEPA and subsequent CEQ guidelines.

In addition to the above "content" criteria, methodological tools should be evaluated in terms of their resource requirements, replicability, and flexibility. The following considerations, used in arriving at the generalized ratings for these characteristics (shown in Table 14), may be useful in considering the appropriateness of tools. Important specific requirements and limitations are discussed for each tool reviewed in the methodology descriptions below.

• Resource Requirements

1. Data Requirements. Does the methodology require data that is presently available at low retrieval costs?
2. Manpower Requirements. What special skills are required?
3. Time. How much time is required to learn to use and/or actually apply the methodology?
4. Costs. How do costs of using a methodology compare to costs using other tools?
5. Technologies. Are any specific technologies (e.g., computerization) required to use a methodology?

• Replicability

1. Ambiguity. What is the relative degree of ambiguity in the methodology?

TABLE 14. SUMMARY OF METHODOLOGY EVALUATIONS

	Type ¹	Comprehensiveness	Specificity	Isolate Project Impacts	Timing and Duration	Data Sources	Explicit Indicators	Magnitude	Objectivity	Significance	Explicit Criteria	Uncertainty	Risk	Alternatives Comparison	Aggregation	Public Involvement	Affected Parties	Setting Description	Summary Format	Key Issues	NEPA Compliance	Resource Requirements	Replicability	Flexibility
1. Adkins	C	2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
2. Dee (1972)	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
3. Dee (1973)	C-M	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
4. Georgia	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
5. Krauskopf	O	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
6. Leopold	M	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
7. Little	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
8. McHarg	O	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
9. Moore	M	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
10. New York	M	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
11. Smith	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
12. Sorensen	M	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
13. Stover	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
14. Task Force	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
15. Tulsa	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
16. Walton	C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
17. WSCC	A	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

¹Key to types: A = ad hoc
O = overlay
C = checklist
M = matrix
N = network

²Key to evaluation symbols:

• = substantial compliance, low resource needs,
or few replicability-flexibility limitations
• = partial compliance, moderate resource needs, or
moderate limitations
O = no or minimal compliance, high resource needs,
or major limitations
- = aggregation not attempted.

2. Analyst Bias. To what degree will different impact analysts using the methodology tend to produce widely different results?

• Flexibility

1. Scale Flexibility. How applicable is the methodology to projects of widely different scale?
2. Range. For how broad a range of project or impact types is the methodology useful in its present form?
3. Adaptability. How readily can the methodology be modified to fit project situations other than those for which it was designed?

Methodologies were rated for their degree of compliance with the 20 content criteria, their level of resource requirements, and their replicability-flexibility limitations as follows:

- = Substantial compliance, low resource needs, or few replicability-flexibility limitations
- = Partial compliance, moderate resource needs, or moderate limitations
- o = No or minimal compliance, high resource needs, or major limitations.

The resulting ratings, shown in Table 14, should be regarded as subjective judgments only, but do provide a shorthand characterization of the important features of the methodological tools examined.

METHODOLOGY DESCRIPTIONS

The 17 methodologies or tools discussed were examined via the above set of review criteria with results summarized in Table 14 on page 192. A brief description of each methodology follows, discussing the following points.

- The methodology type
- The general approach used
- The range of actions or project types for which the methodology may be applicable
- The comprehensiveness of the methodology in terms of the range of impacts addressed

- The resources required (data, manpower, time, etc).
- The limitations of the methodology (replicability, ambiguity, flexibility)
- Key ideas or particularly useful concepts offered
- Other major strengths and weaknesses as identified by the review criteria.

Because of the brevity and subjectivity of these characterizations, they should not be considered as adequate critiques of the tools examined. They may instead serve as a useful introduction to the range of techniques now evolving.

1. Adkins, William G. and Dock Burke Jr., Interim Report: Social, Economic, and Environmental Factors in Highway Decision Making, research conducted for the Texas Highway Department in cooperation with the U.S. Department of Transportation, Federal Highway Administration: College Station, Texas; Texas Transportation Institute, Texas A&M University (October 1971).

The Adkins methodology is a checklist using a +5 to -5 rating system for evaluating impacts but providing no guidelines for measuring impacts. The approach was developed to deal specifically with the evaluation of highway route alternatives. Because the bulk of parameters used relate directly to highway transportation, the approach is not readily adaptable to other types of projects.

The parameters used are broken down into categories of transportation, environmental, sociological, and economic impact. Environmental parameters are generally deficient in ecological considerations. Social parameters emphasize community facilities and services.

Route alternatives are scored +5 to -5 in comparison to the present state of the project area, not the expected future state without the project. Since the approach uses only subjective relative estimations of impacts, the data, manpower, and cost requirements are very flexible. Reliance on subjective ratings without guidelines for such ratings greatly reduces the replicability of analysis and generally limits the valid use of the approach to a case-by-case comparison of alternatives only.

The detailed listing of social and, to a lesser extent, economic parameters may be helpful for identifying and cataloging impacts in other types of projects. An interesting feature of possible value to other analyses using relative rating systems is the practice of summarizing the number as well as the magnitude of plus and minus ratings for each impact category. The number of pluses and minuses may be a more reliable indicator for alternative comparison since it is less subject to the arbitrariness of subjective weighting. These summarizations are additive and thus implicitly weigh all impacts equally.

2. Dee, Norbert, et al, Environmental Evaluation System For Water Resources Planning, report to the U.S. Bureau of Reclamation, Columbus, Ohio: Battelle Memorial Institute (January 1972).

This methodology is a checklist procedure emphasizing quantitative impact assessment. It was designed for major water resource projects but most parameters used are also appropriate for other types of projects. Seventy-eight specific environmental parameters are defined within the four categories of ecology, environmental pollution, aesthetics, and human interest. The approach does not deal with economic or secondary impacts and social impacts are only partially covered within the human interest category.

Impacts are measured via specific indicators and formulas defined for each parameter. Parameter measurements are converted to a common base of "environmental quality units" through specified graphs or value functions. Impacts can be aggregated using a set of preassigned weights.

The resource requirements are rather high, particularly data requirements. These requirements probably restrict the use of the approach to major project assessments.

The approach emphasizes explicit procedures for impact measurement and evaluation and should therefore produce highly replicable results. Both spatial and temporal aspects of impacts are noted and explicitly weighted in the assessment. Public participation, uncertainty, and risk concepts are not dealt with. An important idea of the approach is the highlighting of key impacts via a "red flag" system.

3. Dee, Norbert, et al., Planning Methodology for Water Quality Management: Environmental Evaluation System, Columbus, Ohio: Battelle Memorial Institute (July 1973).

This unique methodology of impact assessment defies ready classification since it contains elements of checklist, matrix, and network approaches. Areas of possible impacts are defined by a hierarchical system of four categories (ecology, physical/chemical, aesthetic, social), 19 components and 64 parameters. An interaction matrix is presented to indicate which activities associated with water quality treatment projects generally impact which parameters. The range of parameters used is comprehensive, excluding only economic variables.

Impact measurement incorporates two important elements. A set of "ranges" is specified for each parameter to express impact magnitude on a scale from zero to one. The ranges assigned to each parameter within a component are then combined by means of an "environmental assessment tree" into a summary environmental impact score for that component. The significance of impacts on each component is quantified by a set of assigned weights. A net impact can be obtained for any alternative by multiplying each component score by its weight factor and summing across components.

The key features of the methodology are its comprehensiveness, its explicitness in defining procedures for impact identification and scoring, and its flexibility in allowing use of best available data.

Sections of the report explain the several uses of the methodology in an overall planning effort and discuss means of public participation. The data, time, and cost requirements of the methodology when used for impact assessment are moderate, though a small amount of training would be required to familiarize users with the techniques used.

Because of its explicitness, the methodology possesses only minor ambiguities and should be highly replicable. Because the environmental assessment trees are developed specifically for water treatment facilities, the methodology cannot be adapted to other types of projects without reconstructing the trees though the parameters could be useful as a simple checklist.

One potentially significant obstacle to use of the approach is the difficulty of explaining the procedures to the public. Regardless of the validity of the "trees", they are unfamiliar devices developed by highly specialized multivariant analysis techniques and public acceptance of conclusions reached by their use may be low.

4. Institute of Ecology, University of Georgia, "Optimum Pathway Matrix Analysis Approach to the Environmental Decision Making Process: Test case: Relative Impact of Proposed Highway Alternatives", Athens, Georgia: University of Georgia, Institute of Ecology (1971) (mimeographed).

The "Georgia" methodology incorporates a checklist of 56 environmental components. Measurable indicators are specified for each component. The actual values of alternative plan impacts on a component are normalized and expressed as a decimal of the largest impact (on that one component). These normalized values are multiplied by a subjectively determined weighting factor. This factor is the sum of one times a weight for "initial" effects plus ten times a weight for "long-term" effects.

The methodology is used to evaluate highway project alternatives and the components listed are not suitable for other types of projects. A wide range of impact types are analyzed including land use, social, aesthetics, and economic impacts.

The lower replicability of the analysis produced by using subjectively determined weighting factors is compensated for by conducting several passes at the analysis, and incorporating randomly generated error variation in both actual measurements and weights. This procedure provides a basis for testing the significance of differences in total impact scores between alternatives.

The procedures for normalizing or scaling measured impacts to obtain commensurability, and testing of significant differences between alternatives are notable features of potential value to other impact analyses and methodologies. These ideas may be useful whenever several project alternatives can be identified and compared.

The Georgia methodology places rather high resource demands on the user since computerization is necessary to generate random errors and make the large number of repetitive calculations.

5. Krauskopf, Thomas M., and Dennis C. Bunde, "Evaluation of Environmental Impact Through a Computer Modelling Process", Environmental Impact Analysis: Philosophy and Methods, (eds.) Robert Ditton and Thomas Goodale, Madison, Wisconsin: University of Wisconsin Sea Grant Program (1972), pp. 107-125.

This methodology employs an overlay technique via computer mapping. Data on a large number of environmental characteristics are collected and stored in the computer on a grid system of 1 km square cells. Highway route alternatives can either be evaluated by the computer (by noting the impacts on intersected cells) or new alternatives may be generated via a program identifying the route of least impact.

The environmental characteristics used are rather comprehensive, particularly as regards land use and physiographic characteristics. Though the methodology was developed and applied to a highway setting, it is adaptable, with relatively small changes in characteristics examined, to other project types with geographically well defined and concentrated impacts. Because the approach requires considerable amounts of data on the project region, it is not practical for the analysis of programs of broad geographical scope. The high manpower-skill, money, and computer technology requirements of the approach may also make it impractical at the present time for any but major projects, or in situations where a statewide, computerized data base exists (New York, Minnesota, Iowa, etc.).

The estimation of impact importance is done through the specification of subjective weights. Because the approach is computerized, the effects of several alternative weighting schemes can be readily analyzed.

The methodology is attractive on several viewpoints. It allows a demonstration of which weighted characteristics are central to a particular alternative route; it presents a readily understandable graphic representation of impacts and alternatives; it easily handles several subjective weighting systems; the incremental costs of considering or generating additional alternatives is low; and it fits well with developing regional and statewide data bank systems.

The mechanics of the approach--how impacts are measured and combined--are not readily apparent from the reference cited. Considerable training beyond the information available in this reference would be required to use the approach.

6. Leopold, Luna B., et al., A Procedure for Evaluating Environmental Impact, Geological Survey Circular 645, Washington: Government Printing Office (1971).

This is an open-cell matrix approach identifying 100 project activities and 88 environmental characteristics or conditions. For each action involved in a project, the analyst evaluates the impact on every impacted environmental characteristic in terms of impact magnitude and significance. These evaluations are subjectively determined by the analyst. Ecological and physical-chemical impacts are treated comprehensively, social and indirect impacts are less well handled, and economic and secondary impacts are not addressed.

Because the assessments made are subjective, resource requirements of the approach are very flexible. The approach was not developed in reference to any specific type of project and may be broadly applied with some alterations.

Guidelines for use of the approach are minimal and several important ambiguities are likely in the definition and separation of impacts. The reliance on subjective judgment, again without guidelines, reduces the replicability of the approach.

The approach is chiefly valuable as a means of identifying project impacts and as a display format for communicating results of an analysis.

7. Arthur D. Little, Inc., Transportation and Environment: Synthesis for Action: Impact of National Environmental Policy Act of 1969 on the Department of Transportation, Vol. 3, Options for Environmental Management, prepared for Office of the Secretary, Department of Transportation (July 1971).

This is less a complete methodology than an overview discussion of the kinds of impacts that may be expected to occur from highway projects and the measurement techniques that may be available to handle some of them. A quite comprehensive list of impact types and the stages of project development at which each may occur are presented. As broad categories, the impact types identified are useful for other projects as well as for highways.

The approach suggests the separate consideration of an impact's amount, effect (public response), and value. Some suggestions are offered for measuring the amount of impact within each of seven general categories: noise, air quality, water quality, soil erosion, ecologic, economic, and sociopolitical impacts.

Five possible approaches to the handling of impact significance are presented. Three of these are "passive" (requiring no agency action) such as "reliance on the emergence of controversy". The other two involve the use of crude subjective weighting scales. No specific suggestions are made for the aggregation of impacts either within or between categories.

In general, the reference cited is a useful discussion of some of the important issues of impact analysis, particularly as they apply to transportation projects, but does not present a complete analytical technique.

8. McHarg, Ian., "A Comprehensive Highway Route-Selection Method", Highway Research Record, Number 246, 1968, pp. 1-15, or McHarg, Design With Nature, Garden City, New York: Natural History Press, 1969, pp. 31-41.

The McHarg approach is a system employing transparencies of environmental characteristics overlaid on a regional base map. Eleven to sixteen environmental and land use characteristics are mapped. The maps represent three levels of the characteristics, based upon "compatibility with the highway". These references do not indicate how this compatibility is to be determined but available documentation is cited.

This approach is basically an earlier, noncomputerized version of the ideas presented in the Krauskopf reference. Its basic value is as a method for screening alternative project sites or routes. Within this limited use, it is applicable to a variety of project types.

Limitations of the approach include its inability to quantify as well as identify possible impacts and its implicit weighting of all characteristics mapped.

Resource requirements of the McHarg approach are somewhat less demanding, in terms of data, than those of the Krauskopf approach because information is not directly quantified, only categorized into three levels. High degrees of skill and training are required, however, to prepare the map overlays.

The approach seems most useful as a "first cut method" of identifying and sifting out alternative project sites, preliminary to detailed impact analysis.

9. Moore, John L., et al., A Methodology for Evaluating Manufacturing Environmental Impact Statements for Delaware's Coastal Zone, Report to the State of Delaware, Columbus, Ohio: Battelle Memorial Institute (June 1973).

This approach was not designed as a method for impact analysis but its principles could be adapted for such use. It employs a network approach, linking a list of manufacturing-related activities-to potential environmental alterations-to major environmental effects, and finally-to human uses affected. The primary strength of the set of linked matrices is their utility in displaying cause-condition-effect networks and tracing out secondary impact chains.

Such networks are useful primarily for identifying impacts and the issues of impact magnitude and significance are addressed only in terms of high, moderate, low, or negligible damage. As a result of these subjective evaluations the approach would have low replicability as an assessment technique. For such a use, guidelines would likely need to be proposed to define the evaluation categories.

The approach incorporates indicators especially tailored to manufacturing facilities in a coastal zone though most indicators would also be pertinent to other types of projects.

The approach would perhaps be valuable as a visual summary of an impact analysis for communication to the public and decision makers.

10. Central New York Regional Planning and Development Board, Environmental Resources Management, prepared for Department of HUD (October 1972) (available through the National Technical Information Service PB 217-517).

This methodology employs a matrix approach to assess in simple terms the major and minor, direct and indirect impacts of certain water related construction activities. It is designed primarily to measure only the physical impacts of water resource projects in a watershed, and is based on an identification of the specific, small-scale component activities that are included in any project. Restricted to physical impacts on nine

different types of watershed areas (e.g., wetlands) and fourteen types of activities (e.g., tree removal), the procedure indicates four possible levels of impact-receptor interactions (major direct through minor indirect). Low to moderate resources in terms of time, money, or personnel are required for the methodology, due principally to its simple way of quantification (major versus minor impact). However, the procedure is severely limited in its ability to compare different projects or the magnitude of different impacts. There is no spatial or temporal differentiation, hence the full range of impacts cannot be assessed. Impact uncertainty and high damage-low probability impacts are also not considered. Only two levels of the magnitude of an impact are identified while the importance of the impacts are not assessed, resulting in moderate replicability. The lack of objective evaluation criteria may produce ambiguous results. NEPA requirements for impact assessments are not directly met by this procedure.

The value of this methodology is less in the actual assessment of the quantitative impacts of a potential project than in a "capability rating system" which determines recommended development policies based on existing land characteristics. Thus, guidelines on desirable and undesirable activities with respect to the nine types of watershed areas are used to map a region in terms of the optimum land use plan. The actual mapping procedure is not described, however, and hence that aspect of the impact assessment methodology cannot be evaluated here.

11. Smith, William L., "Quantifying the Environmental Impact of Transportation Systems", Van Doren-Hazard-Stallings-Schnacke, Topeka, Kansas (undated) (mimeographed).

The Smith approach, as developed for highway route selection, is a checklist system based on the concepts of probability and supply-demand. The approach attempts to identify the alternative with least social cost to environmental resources and maximum social benefit to system resources. Environmental resources elements are listed as: agriculture, wildlife conservation, interference, noise, physical features, and replacement. System resources elements are listed as: aesthetics, cost, mode interface, and travel desires. For each element, categories are defined and used to classify zones of the project area. Numerical probabilities of supply and of demand are then assigned to each zone for each element. These are multiplied to produce a "probability of least

social cost" (or maximum social benefit). These least social cost probabilities are then multiplied across the elements to produce a total for the route alternative under examination.

The approach is tailored and perhaps limited to project situations requiring comparison of siting alternatives. The range of environmental factors examined is very limited, but presumably could be expanded to cover more adequately ecological, pollution, and social considerations.

Since procedures for determining supply and demand probabilities are not described, it is difficult to anticipate the amounts of data, manpower and money required to use the approach. The primary limitations of this methodology are difficulties inherent in assigning probabilities, particularly demand probabilities, and the implicitly equal weightings assigned to each element analyzed when multiplying to yield an aggregate score for an alternative.

12. Sorensen, Jens, A Framework for Identification and Control of Resource Degradation and Conflict in the Multiple Use of the Coastal Zone, Berkeley: University of California, Department of Landscape Agriculture (1971), and Sorensen and James E. Pepper, Procedures for Regional Clearinghouse Review of Environmental Impact Statements -- Phase Two, report to the Association of Bay Area Governments (April 1973).

These two publications present a network approach usable for environmental impact analysis. The approach is not a full methodology but rather a guide to the identification of impacts. Several potential uses of the California coastal zone are examined through networks relating uses-to causal factors (project activities)-to first order condition changes-to second and third order condition changes, and finally-to effects. The major strength of the approach is its ability to identify the pathways by which both primary and secondary environmental impacts are produced.

The second reference also indicates types of data relevant to each effect identified, though no specific measurable indicators are suggested. In this reference some general criteria for identifying projects of regional significance are suggested, based on project size and types of impacts generated, particularly land use impacts.

Because the preparation of the required detailed networks is a major undertaking, the approach is presently limited to some commercial, residential, and transportation uses of the California coastal zone for which networks have been prepared. An agency wishing to use the approach in other circumstances might develop the appropriate networks for reference in subsequent environmental impact assessments.

13. Stover, Lloyd V., Environmental Impact Assessment: A Procedure, Miami, Florida: Sanders and Thomas, Inc. (1972).

This methodology is a checklist procedure for a general quantitative evaluation of environmental impacts from development activities. The type and range of these activities is not specified, but is believed to be comprehensive. Fifty different impact parameters are sufficient to include most possible effects, and thereby allow much flexibility. Subparameters indicate specific impacts, but there is no indication of how the individual measures are aggregated into a single parameter value. While spatial differences in impacts are not indicated, both initial and future impacts are included and explicitly compared. Resource requirements are moderate to heavy, especially in terms of an interdisciplinary personnel team which grows as more subparameters are included, requiring additional expertise in specific areas. However, the actual measurements are not based on specific criteria and are only partially quantitative, with seven possible values ranging from an extremely beneficial impact to an extremely detrimental one. Therefore, there is potential for ambiguous and subjective results, with only moderate replicability. Impact areas are implicitly assumed to be of equal importance. A specific methodology is mentioned for choosing the optimum alternative in terms of benefits and adverse effects. The procedure for alternatives comparison may be the most interesting aspect of the procedure, with results given in terms of the proportional significance of an impact vis-a-vis other potential alternatives. There is no explicit mention of either public involvement in the process, or environmental risks.

The impact assessment procedure is presented as only one step in a total evaluation scheme which includes concepts of dynamic ecological stability and other ideas. An actual description of the entire process is not included, however.

14. Multiagency Task Force, "Guidelines for Implementing Principles and Standards for Multiobjective Planning of Water Resources", Review Draft, Washington: U.S. Bureau of Reclamation (1972).

The Task Force approach is an attempt to coordinate features of the Water Resources Council's Proposed Principles and Standards for Planning Water and Related Land Resources with requirements of NEPA. It develops a checklist of environmental components and categories organized in the same manner as the WEC Guidelines. The categories of potential impacts examined deal comprehensively with biological, physical, cultural, and historical resources, and pollution factors but do not treat social or economic impacts. Impacts are measured in quantitative terms where possible and also rated subjectively on "quality" and "human influence". In addition, uniqueness and irreversibility considerations are included where appropriate. Several suggestions for summary tables and bar graphs are offered as communications aids.

The approach is general enough to have wide applicability to various types of projects, though its impact categories are perhaps better tailored to rural than urban environments. No specific data or other resources are required to conduct an analysis, though an interdisciplinary project team is specified to assign the subjective weightings. Since quality, human influence, uniqueness, and irreversibilities are all subjectively rated using general considerations only, results produced by the approach may be highly variable. Significant ambiguities include a generally inadequate explanation of how human influence impacts are to be rated and interpreted.

Key ideas incorporated in the approach include explicit identification of the without-project environment as distinct from present conditions, and use of uniqueness rating system for evaluating quality and human influence (worst known, average, best known, etc). The methodology is unique among those examined in not labeling impacts as environmental benefits or costs but only as impacts to be valued by others. The approach also argues against the aggregation of impacts.

15. Tulsa District, U.S. Army Corps of Engineers,
Matrix Analysis of Alternatives for Water Resource
Development, draft technical paper (July 31, 1972).

Despite the title, this methodology can be considered a checklist under the definitions used here since, though a display matrix is used to summarize and compare the impacts of project alternatives, impacts are not linked to specific project actions. The approach was developed to deal specifically with reservoir construction projects but could be readily adapted to other project types.

Potential impacts are identified within three broad objectives: environmental quality, human life quality, and economics. For each impact type identified, a series of factors are described, indicating possible measurable indicators. Impact magnitude is not measured in physical units but by a relative impact system. This system assigns the future state of an environmental characteristic without the project a score of zero; then assigns the project alternative possessing the greatest impact on that characteristic a score of +5 (for positive impact), or -5 (for negative impact). All other alternatives are assigned scores between 0 and 5 by comparison. The raw scores thus obtained are multiplied by weights determined subjectively by the impact analysis team.

Like the Georgia approach, the Tulsa methodology tests for the significance of differences between alternatives by introducing error factors and conducting repeated runs. The statistical manipulations are different from those used in the Georgia approach, however, and considered by the Corps' writers to be more valid.

Resource requirements of the Tulsa methodology are variable. Since specific types or levels of data are not required, data needs are quite flexible. The consideration of error, however, requires specific skills and computer facilities.

The major limitations of the approach, aside from the required computerization, are the lack of clear guidelines on exactly how to measure impacts and the lack of guidance on how the future no-project state is to be defined and described in the analysis. Without careful description of the assumptions made, replicability of analyses made using the approach may be low since only relative measures are used. Since all

measurements are relative, it may also be difficult in some cases to deal with impacts that are not clearly definable as gains or losses.

The key ideas of wider interest incorporated in the Tulsa approach include reliance on relative rather than absolute impact measurement, statistical tests of significance with error introduction, and specific use of the no-project condition, as a base line for impact evaluation.

16. Walton, L. Ellis, Jr., and James E. Lewis, A Manual for Conducting Environmental Impact Studies, Virginia Highway Research Council (January 1971) (available through the National Technical Information Service PB-210 222).

The Walton methodology is a checklist, unique in its almost total reliance on social impact categories and strong public participation. The approach was developed for the evaluation of highway alternatives and identifies different impact analysis procedures for the conceptual, corridor, and design states of highway planning. All impacts are measured by either their dollar value or a weighted function of the number of persons affected. (The weights used are to be determined subjectively by the study team.) The basis for most measurements is a personal interview with a representative of each facility or service impacted.

Resource requirements for such a technique are highly sensitive to project scale. The extensive interviewing required may make the approach impractical for many medium-size or large projects because agencies preparing impact statements seldom have the necessary manpower or the money to contract for such extensive interviewing.

Analyses produced by the approach may have very poor replicability due to the lack of specific data used and the criticality of the decision regarding boundaries of the analysis since many impacts are measured in numbers of people affected. There is also no means of systematically taking into account the extent to which these people are affected.

The key ideas of broader interest put forth by the approach are the use of only social impacts without direct consideration of other impacts (pollution, ecology, etc), the heavy dependence on public involvement and specific suggestions on how the public may be involved, and the recognition of the need for different analyses of different stages of project development.

17. Western Systems Coordinating Council, Environmental Committee, Environmental Guidelines (1971). (Mr. Robert Coe, Southern California Electric Company, Environmental Committee Chairman.)

The Environmental Guidelines are intended primarily as a planning tool for siting power generation and transmission facilities. However, they address many of the concerns of environmental impact analysis and have been used in the preparation of impact statements. Viewed as an impact assessment methodology, the approach is an ad hoc procedure, suggesting general areas and types of impacts but not listing specific parameters to examine.

The approach considers a range of pollution, ecological, economic (business economics), and social impacts but does not address secondary impacts such as induced growth, or energy use patterns. The format of the approach is an outline of considerations important to the selection of sites for each of several types of facilities -- e.g., thermal generating plants, transmission lines, hydroelectric and pumped storage, and substations. An additional section offers suggestions for a public information program.

Since the approach does not suggest specific means of measuring or evaluating impacts no particular types of data or resources are required. The application of this approach is limited to the siting of electric power facilities with little carry over to other types of projects.

ASSESSMENT METHODOLOGIES IN IMPACT STATEMENTS

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As a part of the review of methodologies for environmental impact assessment, 67 statements were examined for the methodologies used. The statements were distributed as follows (see full listing at the end of the section): Bureau of Reclamation 15, Army Corps of Engineers 22, Tennessee Valley Authority 14, Soil Conservation Service 13, and Federal Power Commission 3.

None of the statements examined employed any of the 17 methodologies reviewed, nor did they employ other identifiable systems of impact assessment. Without exception, the statements utilized techniques that must be characterized as ad hoc, or less frequently, simple check lists. These approaches characteristically addressed the four basic elements of impact assessment as follows.

Impact Identification

Impacts were generally identified solely from the perceptions of the agency staff preparing the statement, with general guidance from agency procedural guidelines. There was no evidence of any attempt to employ either exhaustive lists of potentially impacted environmental features or lists of impacts typically associated with specific types of projects. As a result, the statements exhibited great variability in the types of impacts dealt with. Impacts on hydrologic systems, wildlife, water and air quality were nearly always covered. Impacts on ecological systems characteristics (diversity, productivity), land use, induced growth, economics, social-cultural patterns, and all types of secondary impacts were more rarely addressed.

Impact Measurement

The only generalization possible regarding impact measurement techniques employed in the statements reviewed is that impacts were

universally expressed in terms of available data only. No evidence of the collection of any original data to assess environmental impacts was seen. As a result, impacts were expressed at greatly varying levels of objectivity and precision, from "may affect air quality" to detailed inventories of species population changes expected and acres of land use shifts. Generally, impact magnitudes were not separated from significance.

Impact Evaluation

No systematic means of reporting impact significance was found in the statements examined. Most estimates of significance were highly subjective conclusions of the agency staff. The only commonly employed aspect of significance used was "uniqueness", occasionally employed in discussing impacts on wildlife, historical and archeological features, and aesthetics. The statements exhibited no consistent frame of reference (local, regional, national) in assessing impact significance and no systematic consideration of the timing of effects.

In contrast to the heavy emphasis placed on aggregating impacts into net scores exhibited by several of the methodologies examined, the 67 impact statements universally ignored aggregation. Impacts were simply listed in paragraph or outline form, though such listing became long and complex for some major projects such as the Central Arizona Project.

Impact Communication

Attempts to summarize and communicate conclusions were generally limited to a mechanical adherence to the points of NEPA, and a one-page statement summary. In only one case (Bonneville Unit, Central Utah Project, BuRec) were simple summary comparisons of alternatives prepared. No statement included a point-by-point comparison of the preferred project plan and alternatives. Impacts were likewise never summarized in terms of affected parties.

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SECTION VIII

ENVIRONMENTAL IMPACT STATEMENTS REVIEWED

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Department of the Interior, Bureau of Reclamation, "Final Environmental Impact Statement, Proposed Central Arizona Project" (September 26, 1972).

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